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U S DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371

ATTORNEY'S DOCKET NUMBER
41002

U.S APPLICATION NO. (If known, see 37 CFR 1.5)
09/673266

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/EP98/02167	14 April 1998	

TITLE OF INVENTION
Echo Phase Offset Correction in a Multi-Carrier Demodulation System

APPLICANT(S) FOR DO/EO/US
Ernst Eberlein, Sabah Badri, Stefan Lipp, Stephan Buchholz, Albert Heuberger, Heinz Gerhaeuser, Robert Fischer

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☑ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. ☐ This express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).
4. ☑ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date.
5. ☑ A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. ☑ is transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☑ has been transmitted by the International Bureau.
   c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☐ A translation of the International Application into English (35 U.S.C. 371(c)(2)).
7. ☑ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371(c)(3))
   a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau).
   b. ☐ have been transmitted by the International Bureau.
   c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   d. ☑ have not been made and will not be made.
8. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
9. ☐ An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. ☐ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11. to 16. below concern document(s) or information included:

11. ☐ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. ☑ A FIRST preliminary amendment.
    ☐ A SECOND or SUBSEQUENT preliminary amendment.
14. ☑ A substitute specification.
15. ☐ A change of power of attorney and/or address letter.
16. ☑ Other items or information:
    (a) Copy of International Application as filed (14 April 1998).
    (b) Copy of International Search Report (12 January 1999).
    (c) Copy of Published International Application (21 October 1999).
    (d) Copy of International Preliminary Examination Report (19 July 2000).

529 Rec'd PCT/PTO 13 OCT 2000

U.S. APPLICATION NO. (if known, see 37 CFR 1.5)	INTERNATIONAL APPLICATION NO	ATTORNEY'S DOCKET NUMBER
09/673266	PCT/EP98/01267	41002

		CALCULATIONS	PTO USE ONLY
17. ☑ The following fees are submitted: **BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) :** Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO .... **$1000.00** International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO....... **$860.00** International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO .... **$710.00** International preliminary examination fee paid to USPTO (37 CFR 1.482) but all claims did not satisfy provisions of PCT Article 33(1)-(4)........... **$690.00** International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(1)-(4)................ **$100.00**			
ENTER APPROPRIATE BASIC FEE AMOUNT =		$ 860.00	
Surcharge of **$130.00** for furnishing the oath or declaration later than ☐ 20 ☑ 30 months from the earliest claimed priority date (37 CFR 1.492(e)).		$ 130.00	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	18 - 20 =	0	X **$18.00**	$ 0.00	
Independent claims	4 - 3 =	0	X **$80.00**	$ 80.00	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ **$270.00**	$ 0.00	
TOTAL OF ABOVE CALCULATIONS =				$ 1,070.00	
Reduction of 1/2 for filing by small entity, if applicable. A Small Entity Statement must also by filed (Note 37 CFR 1.9, 1.27, 1.28).				$ (0.00)	
SUBTOTAL =				$ 1,070.00	
Processing fee of **$130.00** for furnishing the English translation later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492(f)). +				$ 0.00	
TOTAL NATIONAL FEE =				$ 1,070.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). **$40.00** per property +				$ 0.00	
TOTAL FEES ENCLOSED =				$ 1,070.00	
				Amount to be refunded:	$
				charged:	$

a. ☑ A check in the amount of $ 1,070.00 to cover the above fees is enclosed.

b. ☐ Please charge my Deposit Account No. ________ in the amount of $________ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. ☑ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 18-2220. A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

Roylance, Abrams, Berdo & Goodman, L.L.P.
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John E. Holmes
SIGNATURE

John E. Holmes
NAME

29,392
REGISTRATION NUMBER

41002 PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:	
Ernst Eberlein et al.	Group Art Unit:
Serial No.: Not Assigned	Examiner:
Filed: Herewith	
For: Echo Phase Offset Correction in a Multi-Carrier Demodulation System	

PRELIMINARY AMENDMENT

Assistant Commissioner for Patents
Washington, D.C. 20231

Sir:

This Preliminary Amendment is being filed concurrently with the U.S. national stage entry under 35 U.S.C. § 371 of International Application No. PCT/EP98/02167, which has an International Filing Date of April 14, 1998. Prior to examination and calculation of the filing fees, please amend the national stage application as follows:

IN THE TITLE OF THE INVENTION:

Please delete the title used during the international stage and substitute the following new title: –Echo Phase Offset Correction in a Multi-Carrier Demodulation System--.

IN THE SPECIFICATION:

Please delete the current specification, comprising pages 1-30 and 44 (as amended in the International Preliminary Examination Report dated July 19, 2000) and replace it with the accompanying substitute specification.

IN THE CLAIMS:

Please cancel claims 1-18 annexed to the International Preliminary Examination Report dated July 19, 2000, and substitute the following new claims 19-36:

19. A method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties related to the transmitted information from said decoded phase shift;

averaging said echo phase offsets in order to generate an averaged offset; and

correcting each decoded phase shift based on said averaged offset.

20. The method according to claim 19, wherein said step of differential phase decoding comprises the step of differential phase decoding phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

21. The method according to claim 19, wherein said step of differential phase decoding comprises the step of differential phase decoding phase shifts based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

22. The method according to claim 19, further comprising a step of comparing an absolute value of a symbol associated with a respective decoded phase shift with a threshold, wherein only phase shifts having associated therewith symbols having an absolute value exceeding said threshold are used in said step of averaging said echo phase offsets.

23. A method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, said phase shifts defining signal points in a complex plane;

pre-rotating said signal points into the sector of said complex plane between -45° and +45°;

determining parameters a, b of a straight line approximating the location of said pre-rotated signal points in said complex plane;

determining a phase offset based on said parameters a, b; and

correcting each decoded phase shift based on said phase offset.

24. The method according to claim 23, wherein said simultaneous carriers are equally spaced in the frequency axis direction.

25. The method according to claim 23, wherein said step of determining said parameters a, b comprises a least squares method for selecting those parameters which minimize the deviations of said pre-rotated signal points from said straight line.

26. The method according to claim 25, wherein said parameters a, b are determined as follows:

$$b = \frac{\sum_{i=1}^{K} (x_i - \overline{x}) \cdot y_i}{\sum_{i=1}^{K} (x_i - \overline{x})^2}, \quad a = \overline{y} - \overline{x} \cdot b$$

$$\overline{x} = \frac{1}{N} \sum_{i=1}^{K} x_i, \quad \overline{y} = \frac{1}{N} \sum_{i=1}^{K} y_i$$

wherein x and y designate the coordinates of the signal points in the complex plane,

i is an index from 1 to N, and

K is the number of signal points.

27. The method according to claim 26, wherein said phase offset φ_k is determined as follows:

$$\varphi_k = \begin{cases} -\operatorname{a\,tan}\left(\dfrac{a + b\sqrt{|v_k|^2(1 + b^2) - a^2}}{-ab + \sqrt{|v_k|^2(1 + b^2) - a^2}} \right) & \text{for} \quad |v_k|^2 \geq \dfrac{a^2}{1 + b^2} \\ \operatorname{a\,tan}\left(\dfrac{1}{b} \right) & \text{for} \quad |v_k|^2 < \dfrac{a^2}{1 + b^2} \end{cases}$$

wherein v_k is a given decision variable.

28. An echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift comprising means for eliminating phase shift uncertainties related to the transmitted information from said decoded phase shift;

means for averaging said echo phase offsets in order to generate an averaged offset; and

means for correcting each decoded phase shift based on said averaged offset.

29. The device according to claim 28, wherein said differential phase decoder is adapted for decoding said phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

30. The device according to claim 28, further comprising means for comparing an absolute value of a symbol associated with a respective decoded phase shift with a threshold, wherein said means for averaging said phase offsets only uses phase shifts having associated therewith symbols having an absolute value exceeding said threshold.

31. The device according to claim 28, wherein said differential phase decoder is adapted for decoding said phase shifts based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

32. An echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, said phase shifts defining signal points in a complex plane;

means for pre-rotating said signal points into the sector of said complex plane between -45° and +45°;

means for determining parameters a, b of a straight line approximating the location of said pre-rotated signal points in said complex plane;

means for determining a phase offset based on said parameters a, b; and

means for correcting each decoded phase shift based on said phase offset.

33. The device according to claim 32, wherein said differential phase decoder comprises means for decoding phase shifts of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

34. The device according to claim 32, wherein said means for determining said parameters a, b comprises means for performing a least squares method for selecting those parameters which minimize the deviations of said pre-rotated signal points from said straight line.

35. The device according to claim 34, wherein said means for determining said parameters a, b calculates said parameters a, b as follows:

$$b = \frac{\sum_{i=1}^{K} (x_i - \overline{x}) \cdot y_i}{\sum_{i=1}^{K} (x_i - \overline{x})^2}, \quad a = \overline{y} - \overline{x} \cdot b$$

$$\overline{x} = \frac{1}{N} \sum_{i=1}^{K} x_i, \quad \overline{y} = \frac{1}{N} \sum_{i=1}^{K} y_i$$

wherein x and y designate the coordinates of the signal points in the complex plane,

i is an index from 1 to N, and

K is the number of signal points.

36. The device according to claim 35, wherein said means for determining said phase offset φ_k calculates said phase offset φ_k as follows:

$$\varphi_k = \begin{cases} -a\tan\left(\dfrac{a + b\sqrt{|v_k|^2(1 + b^2) - a^2}}{-ab + \sqrt{|v_k|^2(1 + b^2) - a^2}}\right) & \text{for} \quad |v_k|^2 \geq \dfrac{a^2}{1 + b^2} \\ a\tan\left(\dfrac{1}{b}\right) & \text{for} \quad |v_k|^2 < \dfrac{a^2}{1 + b^2} \end{cases}$$

wherein v_k is a given decision variable.

REMARKS

By the present Preliminary Amendment, claims 1-18 annexed to the International Preliminary Examination Report dated July 19, 2000 are being cancelled and replaced with new claims 19-36. In the new claims, multiple dependencies and parenthetical reference numerals have been eliminated.

A substitute specification is being submitted to facilitate processing of this application. A marked-up copy of the substitute specification is also being provided to show the new changes which are beyond those previously made during the international stage. The substitute specification contains no new matter.

Early and favorable action on this application is respectfully requested. Should the Examiner have any questions, the Examiner is invited to contact the undersigned attorney at the local telephone number listed below.

Respectfully submitted,

John E. Holmes

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Dated: October 13, 2000

09/673266

DIFFERENTIAL CODING AND CARRIER RECOVERY FOR MULTICARRIER SYSTEMS

FIELD OF THE INVENTION

The present invention relates to methods and apparatus for performing modulation and de-modulation in multi-carrier modulation systems (MCM systems) and, in particular, to methods and apparatus for differential mapping and de-mapping of information onto carriers of multi-carrier modulation symbols in such systems. Furthermore, the present invention relates to methods and apparatus for performing an echo phase offset correction when decoding information encoded onto carriers of multi-carrier modulation symbols in multi-carrier modulation systems.

BACKGROUND OF THE INVENTION

The present invention generally relates to broadcasting of digital data to mobile receivers over time-variant multipath channels. More specifically, the present invention is particularly useful in multipath environments with low channel coherence time, i.e. rapidly changing channels. In preferred embodiments, the present invention can be applied to systems implementing a multicarrier modulation scheme. Multi-carrier modulation (MCM) is also known as orthogonal frequency division multiplexing (OFDM).

In a MCM transmission system binary information is represented in the form of a complex spectrum, i.e. a distinct number of complex subcarrier symbols in the frequency domain. In the modulator a bitstream is represented by a sequence of spectra. Using an inverse Fourier-transform (IFFT) a MCM time domain signal is

produced from this sequence of spectra.

Figure 7 shows a MCM system overview. At 100 a MCM transmitter is shown. A description of such a MCM transmitter can be found, for example, in William Y. Zou, Yiyan Wu, "COFDM: AN OVERVIEW", IEEE Transactions on Broadcasting, vol. 41, No. 1, March 1995.

A data source 102 provides a serial bitstream 104 to the MCM transmitter. The incoming serial bitstream 104 is applied to a bit-carrier mapper 106 which produces a sequence of spectra 108 from the incoming serial bitstream 104. An inverse fast Fourier transform (FFT) 110 is performed on the sequence of spectra 108 in order to produce a MCM time domain signal 112. The MCM time domain signal forms the useful MCM symbol of the MCM time signal. To avoid inter-symbol interference (ISI) caused by multipath distortion, a unit 114 is provided for inserting a guard interval of fixed length between adjacent MCM symbols in time. In accordance with a preferred embodiment of the present invention, the last part of the useful MCM symbol is used as the guard interval by placing same in front of the useful symbol. The resulting MCM symbol is shown at 115 in Figure 7.

A unit 116 for adding a reference symbol for each predetermined number of MCM symbols is provided in order to produce a MCM signal having a frame structure. Using this frame structure comprising useful symbols, guard intervals and reference symbols it is possible to recover the useful information from the MCM signal at the receiver side.

The resulting MCM signal having the structure shown at 118 in Figure 7 is applied to the transmitter front end 120. Roughly speaking, at the transmitter front end 120, a digital/analog conversion and an up-converting of the MCM signal is performed. Thereafter, the MCM signal is transmitted through a channel 122.

Following, the mode of operation of a MCM receiver 130 is shortly described referring to Figure 7. The MCM signal is received at the receiver front end 132. In the receiver front end 132, the MCM signal is down-converted and, furthermore, a digital/analog conversion of the down-converted signal is performed. The down-converted MCM signal is provided to a frame synchronization unit 134. The frame synchronization unit 134 determines the location of the reference symbol in the MCM symbol. Based on the determination of the frame synchronization unit 134, a reference symbol extracting unit 136 extracts the framing information, i.e. the reference symbol, from the MCM symbol coming from the receiver front end 132. After the extraction of the reference symbol, the MCM signal is applied to a guard interval removal unit 138.

The result of the signal processing performed so far in the MCM receiver are the useful MCM symbols. The useful MCM symbols output from the guard interval removal unit 138 are provided to a fast Fourier transform unit 140 in order to provide a sequence of spectra from the useful symbols. Thereafter, the sequence of spectra is provided to a carrier-bit mapper 142 in which the serial bitstream is recovered. This serial bitstream is provided to a data sink 144.

As it is clear from Figure 7, every MCM transmitter 100 must contain a device which performs mapping of the transmitted bitstreams onto the amplitudes and/or phases of the sub-carriers. In addition, at the MCM receiver 130, a device is needed for the inverse operation, i.e. retrieval of the transmitted bitstream from the amplitudes and/or phases of the sub-carriers.

For a better understanding of MCM mapping schemes, it is preferable to think of the mapping as being the assignment of one ore more bits to one or more sub-carrier symbols in the time-frequency plane. In the following, the term symbol

or signal point is used for the complex number which represents the amplitude and/or phase modulation of a subcarrier in the equivalent baseband. Whenever all complex numbers representing all subcarrier symbols are designated, the term MCM symbol is used.

DESCRIPTION OF PRIOR ART

In principle, two methods for mapping the bitstream into the time-frequency plane are used in the prior art:

A first method is a differential mapping along the time axis. When using differential mapping along the time axis one or more bits are encoded into phase and/or amplitude shifts between two subcarriers of the same center frequency in adjacent MCM symbols. Such an encoding scheme is shown in Figure 8. The arrows depicted between the sub-carrier symbols correspond to information encoded in amplitude and/or phase shifts between two subcarrier symbols.

A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 401 (EU147-DAB). A system compliant to this standard uses Differential Quadrature Phase Shift Keying (DQPSK) to encode every two bits into a 0, 90, 180 or 270 degrees phase difference between two subcarriers of the same center frequency which are located in MCM symbols adjacent in time.

A second method for mapping the bitstream into the time-frequency plane is a non-differential mapping. When using non-differential mapping the information carried on a subcarrier is independent of information transmitted on any other subcarrier, and the other subcarrier may differ either in frequency, i.e. the same MCM symbol, or in time, i.e. adjacent MCM symbols. A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 744 (DVB-T). A system compliant to this standard

uses 4,16 or 64 Quadrature Amplitude Modulation (QAM) to assign bits to the amplitude and phase of a subcarrier.

The quality with which transmitted multi-carrier modulated signals can be recovered at the receiver depends on the properties of the channel. The most interesting property when transmitting MCM signals is the time interval at which a mobile channel changes its characteristics considerably. The channel coherence time T_C is normally used to determine the time interval at which a mobile channel changes its characteristics considerably. T_C depends on the maximum Doppler shift as follows:

$$f_{Doppler,max} = v \cdot f_{carrier} \,/\, c \qquad \text{(Eq.1)}$$

with v : speed of the mobile receiver in [m/s]
$f_{carrier}$: carrier frequency of the RF signal [Hz]
c : speed of light ($3 \cdot 10^8$ m/s)

The channel coherence time T_C is often defined to be

$$T_c\Big|_{50\%} = \frac{9}{16\pi f_{Doppler,max}} \quad \text{or} \quad T_c\Big|_{2nd\ Def} = \sqrt{\frac{9}{16\pi f^2_{Dopper,max}}} \qquad \text{(Eq.2)}$$

It becomes clear from the existence of more than one definition, that the channel coherence time Tc is merely a rule-of-thumb value for the stationarity of the channel. As explained above, the prior art time-axis differential mapping requires that the mobile channel be quasi stationary during several MCM symbols periods, i.e. required channel coherence time Tc >> MCM symbol period. The prior art non-differential MCM mapping only requires that the mobile channel be quasi stationary during one symbol interval, i.e. required channel coherence time ≥ MCM symbol period.

Thus, both prior art mapping schemes have specific disadvantages. For differential mapping into time axis direction the channel must be quasi stationary, i.e. the channel must not change during the transmission of two MCM

symbols adjacent in time. If this requirement is not met, the channel induced phase and amplitude changes between MCM symbols will yield an increase in bit error rate.

With non-differential mapping exact knowledge of the phase of each subcarrier is needed (i.e. coherent reception). For multipath channels, coherent reception can only be obtained if the channel impulse response is known. Therefore, a channel estimation has to be part of the receiver algorithm. The channel estimation usually needs additional sequences in the transmitted waveform which do not carry information. In case of rapidly changing channels, which necessitate update of the channel estimation at short intervals, the additional overhead can quickly lead to insufficiency of non-differential mapping.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a method and an apparatus for mapping information onto sub-carrier symbols in a multi-carrier modulation system which allow correct recovering of the information after transmission through a channel even in the case the channel is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for performing a multi-carrier modulation of a bitstream in a digital broadcasting transmitter which allow correct recovering of the bitstream after transmission through a channel even in the case the channel is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for de-mapping information in order to correctly recover the information even in the case a channel through which transmission takes place is not stationary during several MCM symbols.

It is a further object of the present invention to provide a method and an apparatus for performing a demodulation of a multi-carrier modulated signal in a digital broadcasting system in order to correctly recover a bitstream encoded in the multi-carrier modulated signal even in the case a channel through which transmission takes place is not stationary during several MCM symbols.

It is a further object of the present invention to provide methods an apparatus for performing an echo phase offset correction in a multi-carrier demodulation system.

In accordance with a first aspect, the present invention provides a method of mapping information onto at least two simultaneous carriers having different frequencies in a multi-carrier modulation system, the method comprising the step of controlling respective parameters of the at least two carriers such that the information is differentially encoded.

In accordance with a second aspect, the present invention provides a method of performing a multi-carrier modulation of a bitstream in a digital broadcasting transmitter, the method comprising the steps of:

phase shift keying the bitstream by associating a respective phase shift to one or more bits of the bitstream; and

differential phase encoding the phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and the phase shift, the first and second carriers having different frequencies.

In accordance with a third aspect, the present invention provides a method of de-mapping information based on at least two simultaneous encoded carriers having different

frequencies in a multi-carrier demodulation system, the method comprising the step of recovering the information by differential decoding of respective parameters of the at least two carriers.

In accordance with a fourth aspect, the present invention provides a method of performing a demodulation of a multi-carrier modulated signal in a digital broadcasting system, the method comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

recovering bits of a bitstream from said phase shifts.

In accordance with a fifth aspect, the present invention provides a method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties corresponding to codeable phase shifts from the decoded phase shift;

averaging the echo phase offsets in order to generate an averaged offset; and

correcting each decoded phase shift based on the averaged offset.

In accordance with a sixth aspect, the present invention provides a method of performing an echo phase offset

correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

determining a phase offset based on the parameters; and

correcting each decoded phase shift based on the phase offset.

In accordance with a seventh aspect, the present invention provides a mapping device for mapping information onto at least two simultaneous carriers having different frequencies, for a multi-carrier modulation system, the device comprising means for controlling respective parameters of the at least two carriers such that the information is differential encoded.

In accordance with an eighth aspect, the present invention provides a multi-carrier modulator for performing a multi-carrier modulation of a bitstream, for a digital broad-casting transmitter, the modulator comprising:

means for phase shift keying the bitstream by associating a respective phase shift to one or more bits of the bit-stream; and

a differential phase encoder for differential phase

encoding the phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and the phase shift, the first and second carriers having different frequencies.

In accordance with a ninth aspect, the present invention provides a de-mapping device for de-mapping information based on at least two simultaneous encoded carriers having different frequencies, for a multi-carrier demodulation system, the de-mapping device comprising means for recovering the information by differential decoding of respective parameters of the at least two carriers.

In accordance with a tenth aspect, the present invention provides a demodulator for demodulating a multi-carrier modulated signal, for a digital broadcasting system, the demodulator comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for recovering bits of a bitstream from the phase shifts.

In accordance with an eleventh aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties corresponding to codeable phase shifts from the decoded phase shift;

means for averaging the echo phase offsets in order to generate an averaged offset; and

means for correcting each decoded phase shift based on the averaged offset.

In accordance with a twelfth aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

means for pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

means for determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

means for determining a phase offset based on the parameters; and

means for correcting each decoded phase shift based on the phase offset.

The present invention provides a mapping process, suitable for multicarrier (OFDM) digital broadcasting over rapidly changing multipath channels, comprising differential encoding of the data along the frequency axis such that there is no need for channel stationarity exceeding one multicarrier symbol.

When using the inventive mapping process along the frequency axis it is preferred to make use of a receiver algorithm that will correct symbol phase offsets that can be caused by

channel echoes.

The present invention provides a mapping scheme for multi-carrier modulation which renders the transmission to a certain extent independent of rapid changes in the multipath channel without introducing a large overhead to support channel estimation. Especially systems with high carrier frequencies and/or high speeds of the mobile carrying the receiving unit can benefit from the invention.

Thus, the present invention provides a mapping scheme that does not exhibit the two problems of the prior art systems described above. The mapping scheme in accordance with the present invention is robust with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

According to a preferred embodiment of the present invention, the controlled respective parameters of the subcarriers are the phases thereof, such that the information is differentially phase encoded. However, the controlled respective parameters of the subcarriers can be the amplitudes thereof as well, such that the information is differential amplitude encoded.

In accordance with the present invention, mapping is also differential, however, not into time axis direction but into frequency axis direction. Thus, the information is not contained in the phase shift between subcarriers adjacent in time but in the phase shift between subcarriers adjacent in frequency. Differential mapping along the frequency axis has two advantages when compared to prior art mapping schemes. Because of differential mapping, no estimation of the absolute phase of the subcarriers is required. Therefore, channel estimation and the related overhead are not necessary. By choosing the frequency axis as direction for differentially encoding the information bitstream, the requirement that the channel must be stationary during

several MCM symbols can be dropped. The channel only has to remain unchanged during the current MCM symbol period. Therefore, like for non-differential mapping it holds that

required channel coherence time $\geq$ MCM symbol period.

The present invention further provides methods and apparatus for correction of phase distortions that can be caused by channel echoes. As described above, differential mapping into frequency axis direction solves problems related to the stationarity of the channel. However, differential mapping into frequency axis direction may create a new problem. In multipath environments, path echoes succeeding or preceding the main path can lead to systematic phase offsets between subcarriers in the same MCM symbol. In this context, the main path is thought of being the path echo with the highest energy content. The main path echo will determine the position of the FFT window in the receiver of an MCM system.

In preferred embodiments of the present invention, the information will be contained in a phase shift between adjacent subcarriers of the same MCM symbol. If not corrected for, the path echo induced phase offset between two subcarriers can lead to an increase in bit error rate. Therefore, application of the MCM mapping scheme presented in this invention will preferably be used in combination with a correction of the systematic subcarrier phase offsets in case of a multipath channel.

The introduced phase offset can be explained from the shifting property of the Discrete Fourier Transform (DFT):

$$x\left[((n-m))_N\right] \xleftrightarrow{DFT} X[k]e^{-j\frac{2\pi}{N}km} \qquad \text{(Eq.3)}$$

with $x[n]$: sampled time domain signal ($0 \leq n \leq N-1$)

$X[k]$: DFT transformed frequency domain signal ($0 \leq k \leq N-1$)

N : length of DFT

$(...)_N$: cyclic shift of the DFT window in the time
m : length of DFT-Shift in the time domain

Equation 3 shows, that in a multipath channel, echoes following the main path will yield a subcarrier dependent phase offset. After differential demapping in the frequency axis direction at the receiver, a phase offset between two neighboring symbols remains. Because the channel induced phase offsets between differentially demodulated symbols are systematic errors, they can be corrected by an algorithm.

In the context of the following specification, algorithms which help correcting the phase shift are called Echo Phase Offset Correction (EPOC) algorithms. Two such algorithms are described as preferred embodiments for the correction of phase distortions that can be caused by channel echoes. These algorithms yield a sufficient detection security for MCM frequency axis mapping even in channels with echoes close to the limits of the guard interval.

In principle, an EPOC algorithm must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following, preferred embodiments of the present invention will be explained in detail on the basis of the drawings enclosed, in which:

Figure 1 shows a schematic view representing the inventive mapping scheme;

Figure 2 shows a functional block diagram of an embodiment of a mapping device in accordance with the present invention;

Figures 3A and 3B show scatter diagrams of the output of an differential de-mapper of a MCM receiver for illustrating the effect of an echo phase offset correction;

Figure 4 shows a schematic block diagram for illustrating the position and the functionality of an echo phase offset correction unit;

Figure 5 shows a schematic block diagram of an embodiment of an echo phase offset correction device according to the present invention;

Figure 6 shows schematic views for illustrating a projection performed by another embodiment of an echo phase offset correction device according to the present invention;

Figure 7 shows a schematic block diagram of a generic multi-carrier modulation system; and

Figure 8 shows a schematic view representing a prior art differential mapping scheme.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Although the present invention is explained mainly referring to a MCM system using differential phase encoding as generally shown in Figure 7, it is clear that the present invention can be used in connection with different transmission systems using differential amplitude encoding or a combined differential amplitude/phase encoding, for example.

In a preferred embodiment thereof, the present invention is applied to a MCM system as shown in Figure 7. With respect

to this MCM system, the present invention relates to the bit-carrier mapper 106 of the MCM transmitter 100 and the carrier-bit mapper 142 of the MCM receiver 130, which are depicted with a shaded background in Figure 7.

An preferred embodiment of an inventive mapping scheme used by the bit-carrier mapper 106 is depicted in Figure 1. A number of MCM symbols 200 is shown in Figure 1. Each MCM symbol 200 comprises a number of sub-carrier symbols 202. The arrows 204 in Fig. 1 illustrate information encoded between two sub-carrier symbols 202. As can be seen from the arrows 204, the bit-carrier mapper 106 uses a differential mapping within one MCM symbol along the frequency axis direction.

In the embodiment shown in Figure 1, the first sub-carrier (k=0) in an MCM symbol 200 is used as a reference sub-carrier 206 (shaded) such that information is encoded between the reference sub-carrier and the first active carrier 208. The other information of a MCM symbol 200 is encoded between active carriers, respectively.

Thus, for every MCM symbol an absolute phase reference exists. In accordance with Figure 1, this absolute phase reference is supplied by a reference symbol inserted into every MCM symbol (k=0). The reference symbol can either have a constant phase for all MCM symbols or a phase that varies from MCM symbol to MCM symbol. A varying phase can be obtained by replicating the phase from the last subcarrier of the MCM symbol preceding in time.

In Figure 2 a preferred embodiment of a device for performing a differential mapping along the frequency axis is shown. Referring to Figure 2, assembly of MCM symbols in the frequency domain using differential mapping along the frequency axis according to the present invention is described.

Figure 2 shows the assembly of one MCM symbol with the following parameters:

N_{FFT} designates the number of complex coefficients of the discrete Fourier transform, number of subcarriers respectively.

K designates the number of active carriers. The reference carrier is not included in the count for K.

According to Figure 2, a quadrature phase shift keying (QPSK) is used for mapping the bitstream onto the complex symbols. However, other M-ary mapping schemes (MPSK) like 2-PSK, 8-PSK, 16-QAM, 16-APSK, 64-APSK etc. are possible.

Furthermore, for ease of filtering and minimization of aliasing effects some subcarriers are not used for encoding information in the device shown in Figure 2. These subcarriers, which are set to zero, constitute the so-called guard bands on the upper and lower edges of the MCM signal spectrum.

At the input of the mapping device shown in Figure 2, complex signal pairs b0[k], b1[k] of an input bitstream are received. K complex signal pairs are assembled in order to form one MCM symbol. The signal pairs are encoded into the K differential phase shifts phi[k] needed for assembly of one MCM symbol. In this embodiment, mapping from Bits to the 0, 90, 180 and 270 degrees phase shifts is performed using Gray Mapping in a quadrature phase shift keying device 220.

Gray mapping is used to prevent that differential detection phase errors smaller than 135 degrees cause double bit errors at the receiver.

Differential phase encoding of the K phases is performed in a differential phase encoder 222. At this stage of processing, the K phases phi[k] generated by the QPSK Gray

mapper are differentially encoded. In principal, a feedback loop 224 calculates a cumulative sum over all K phases. As starting point for the first computation (k = 0) the phase of the reference carrier 226 is used. A switch 228 is provided in order to provide either the absolute phase of the reference subcarrier 226 or the phase information encoded onto the preceding (i.e. z^{-1}, where z^{-1} denotes the unit delay operator) subcarrier to a summing point 230. At the output of the differential phase encoder 222, the phase information theta[k] with which the respective subcarriers are to be encoded is provided. In preferred embodiments of the present invention, the subcarriers of a MCM symbol are equally spaced in the frequency axis direction.

The output of the differential phase encoder 222 is connected to a unit 232 for generating complex subcarrier symbols using the phase information theta[k]. To this end, the K differentially encoded phases are converted to complex symbols by multiplication with

$$\text{factor} * e^{j*[2*pi*(theta[k] + PHI)]} \qquad \text{(Eq.4)}$$

wherein factor designates a scale factor and PHI designates an additional angle. The scale factor and the additional angle PHI are optional. By choosing PHI = 45° a rotated DQPSK signal constellation can be obtained.

Finally, assembly of a MCM symbol is effected in an assembling unit 234. One MCM symbol comprising N_{FFT} sub-carriers is assembled from N_{FFT}-K-1 guard band symbols which are "zero", one reference subcarrier symbol and K DQPSK subcarrier symbols. Thus, the assembled MCM symbol 200 is composed of K complex values containing the encoded information, two guard bands at both sides of the N_{FFT} complex values and a reference subcarrier symbol.

The MCM symbol has been assembled in the frequency domain. For transformation into the time domain an inverse discrete

Fourier transform (IDFT) of the output of the assembling unit 234 is performed by a transformator 236. In preferred embodiments of the present invention, the transformator 236 is adapted to perform a fast Fourier transform (FFT).

Further processing of the MCM signal in the transmitter as well as in the receiver is as described above referring to Figure 7.

At the receiver a de-mapping device 142 (Figure 7) is needed to reverse the operations of the mapping device described above referring to Figure 2. The implementation of the demapping device is straightforward and, therefore, need not be described herein in detail.

However, systematic phase shifts stemming from echoes in multipath environments may occur between subcarriers in the same MCM symbol. This phase offsets can cause bit errors when demodulating the MCM symbol at the receiver.

Thus, it is preferred to make use of an algorithm to correct the systematic phase shifts stemming from echoes in multi-path environments. Preferred embodiments of echo phase offset correction algorithms are explained hereinafter referring to Figures 3 to 6.

In Figures 3A and 3B, scatter diagrams at the output of a differential demapper of a MCM receiver are shown. As can be seen from Figure 3A, systematic phase shifts between subcarriers in the same MCM symbol cause a rotation of the demodulated phase shifts with respect to the axis of the complex coordinate system. In Figure 3B, the demodulated phase shifts after having performed an echo phase offset correction are depicted. Now, the positions of the signal points are substantially on the axis of the complex coordinate system. These positions correspond to the modulated phase shifts of 0°, 90°, 180° and 270°, respectively.

An echo phase offset correction algorithm (EPOC algorithm) must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

For illustration purposes, one may think of the simplest algorithm possible which eliminates the symbol phase before computing the mean of all phases of the subcarriers. To illustrate the effect of such an EPOC algorithm, reference is made to the two scatter diagrams of subcarriers symbols contained in one MCM symbol in Figures 3A and 3B. This scatter diagrams have been obtained as result of an MCM simulation. For the simulation a channel has been used which might typically show up in single frequency networks. The echoes of this channel stretched to the limits of the MCM guard interval. The guard interval was chosen to be 25% of the MCM symbol duration in this case.

Figure 4 represents a block diagram for illustrating the position and the functionality of an echo phase offset correction device in a MCM receiver. The signal of a MCM transmitter is transmitted through the channel 122 (Figures 4 and 7) and received at the receiver frontend 132 of the MCM receiver. The signal processing between the receiver frontend and the fast Fourier transformator 140 has been omitted in Figure 4. The output of the fast Fourier transformator is applied to the de-mapper, which performs a differential de-mapping along the frequency axis. The output of the de-mapper are the respective phase shifts for the subcarriers. The phase offsets of this phase shifts which are caused by echoes in multipath environments are visualized by a block 400 in Figure 4 which shows an example of a scatter diagram of the subcarrier symbols without an echo phase offset correction.

The output of the de-mapper 142 is applied to the input of an echo phase offset correction device 402. The echo phase

offset correction device 402 uses an EPOC algorithm in order to eliminate echo phase offsets in the output of the de-mapper 142. The result is shown in block 404 of Figure 4, i.e. only the encoded phase shifts, 0°, 90°, 180° or 270° are present at the output of the correction device 402. The output of the correction device 402 forms the signal for the metric calculation which is performed in order to recover the bitstream representing the transmitted information.

A first embodiment of an EPOC algorithm and a device for performing same is now described referring to Figure 5.

The first embodiment of an EPOC algorithm starts from the assumption that every received differentially decoded complex symbol is rotated by an angle due to echoes in the multipath channel. For the subcarriers equal spacing in frequency is assumed since this represents a preferred embodiment of the present invention. If the subcarriers were not equally spaced in frequency, a correction factor would have to be introduced into the EPOC algorithm.

Figure 5 shows the correction device 402 (Figure 4) for performing the first embodiment of an EPOC algorithm.

From the output of the de-mapper 142 which contains an echo phase offset as shown for example in Figure 3A, the phase shifts related to transmitted information must first be discarded. To this end, the output of the de-mapper 142 is applied to a discarding unit 500. In case of a DQPSK mapping, the discarding unit can perform a "$(.)^4$" operation. The unit 500 projects all received symbols into the first quadrant. Therefore, the phase shifts related to transmitted information is eliminated from the phase shifts representing the subcarrier symbols. The same effect could be reached with a modulo-4 operation.

Having eliminated the information related symbol phases in unit 500, the first approach to obtain an estimation would

be to simply compute the mean value over all symbol phases of one MCM symbol. However, it is preferred to perform a threshold decision before determining the mean value over all symbol phases of one MCM symbol. Due to Rayleigh fading some of the received symbols may contribute unreliable information to the determination of the echo phase offset. Therefore, depending on the absolute value of a symbol, a threshold decision is performed in order to determine whether the symbol should contribute to the estimate of the phase offset or not.

Thus, in the embodiment shown in Fig. 5, a threshold decision unit 510 is included. Following the unit 500 the absolute value and the argument of a differentially decoded symbol is computed in respective computing units 512 and 514. Depending on the absolute value of a respective symbol, a control signal is derived. This control signal is compared with a threshold value in a decision circuit 516. If the absolute value, i.e. the control signal thereof, is smaller than a certain threshold, the decision circuit 516 replaces the angle value going into the averaging operation by a value equal to zero. To this end, a switch is provided in order to disconnect the output of the argument computing unit 514 from the input of the further processing stage and connects the input of the further processing stage with a unit 518 providing a constant output of "zero".

An averaging unit 520 is provided in order to calculate a mean value based on the phase offsets φ_i determined for the individual subcarrier symbols of a MCM symbol as follows:

$$\bar{\varphi} = 1/K \sum_{i=1}^{K} \varphi_i \qquad \text{(Eq.5)}$$

In the averaging unit 520, summation over K summands which have not been set to zero in the unit 516 is performed. The output of the averaging unit 520 is provided to a hold unit

522 which holds the output of the averaging unit 520 K times. The output of the hold unit 522 is connected with a phase rotation unit 524 which performs the correction of the phase offsets of the K complex signal points on the basis of the mean value $\bar{\varphi}$.

The phase rotation unit 524 performs the correction of the phase offsets by making use of the following equation:

$$v_k' = v_k \cdot e^{-j\bar{\varphi}} \quad \text{(Eq.6)}$$

In this equation, v_k' designates the K phase corrected differentially decoded symbols for input into the soft-metric calculation, whereas v_k designates the input symbols. As long as a channel which is quasi stationary during the duration of one MCM symbols can be assumed, using the mean value over all subcarriers of one MCM symbol will provide correct results.

A buffer unit 527 may be provided in order to buffer the complex signal points until the mean value of the phase offsets for one MCM symbol is determined. The output of the phase rotation unit 524 is applied to the further processing stage 526 for performing the soft-metric calculation.

With respect to the results of the above echo phase offset correction, reference is made again to Figures 3A and 3B. The two plots stem from a simulation which included the first embodiment of an echo phase offset correction algorithm described above. At the instant of the scatter diagram snapshot shown in Figure 3A, the channel obviously distorted the constellation in a way, that a simple angle rotation is a valid assumption. As shown in Figure 3B, the signal constellation can be rotated back to the axis by applying the determined mean value for the rotation of the differentially detected symbols.

A second embodiment of an echo phase offset correction

algorithm is described hereinafter. This second embodiment can be preferably used in connection with multipath channels that have up to two strong path echoes. The algorithm of the second embodiment is more complex than the algorithm of the first embodiment.

What follows is a mathematical derivation of the second embodiment of a method for echo phase offset correction. The following assumptions can be made in order to ease the explanation of the second embodiment of an EPOC algorithm.

In this embodiment, the guard interval of the MCM signal is assumed to be at least as long as the impulse response h[q], q = 0, 1, ..., Qh-1 of the multipath channel.

At the transmitter every MCM symbol is assembled using frequency axis mapping explained above. The symbol of the reference subcarrier equals 1, i.e. 0 degree phase shift. The optional phase shift PHI equals zero, i.e. the DQPSK signal constellation is not rotated.

Using an equation this can be expressed as

$$a_k = a_{k-1} a_k^{inc} \qquad \text{(Eq.7)}$$

with

k : index k = 1,2,...,K of the active subcarrier;

$a_k^{inc} = e^{j\frac{\pi}{2}m}$: complex phase increment symbol; m=0,1,2,3 is the QPSK symbol number which is derived from Gray encoding pairs of 2 Bits;

$a_0 = 1$: symbol of the reference subcarrier.

At the DFT output of the receiver the decision variables

$$e_k = a_k H_k \qquad \text{(Eq.8)}$$

are obtained with

$$H_k = \sum_{i=0}^{Q_h-1} h[i] \cdot e^{-j\frac{2\pi}{K}ki} \qquad \text{(Eq.9)}$$

being the DFT of the channel impulse response $h[q]$ at position k.

With $|a_k|^2 = 1$ the differential demodulation yields

$$v_k = e_k \cdot e_{k-1}^* = a_k^{inc} H_k H_{k-1}^* \qquad \text{(Eq.10)}$$

For the receiver an additional phase term φ_k is introduced, which shall be used to correct the systematic phase offset caused by the channel. Therefore, the final decision variable at the receiver is

$$v_k' = v_k \cdot e^{j\varphi_k} = a_k^{inc} \cdot e^{j\varphi_k} \cdot H_k \cdot H_{k-1}^* \qquad \text{(Eq.11)}$$

As can be seen from the Equation 11, the useful information a_k^{inc} is weighted with the product $e^{j\varphi_k} \cdot H_k \cdot H^*_{k-1}$ (rotation and effective transfer function of the channel). This product must be real-valued for an error free detection. Considering this, it is best to choose the rotation angle to equal the negative argument of $H_k \cdot H^*_{k-1}$. To derive the desired algorithm for 2-path channels, the nature of $H_k \cdot H^*_{k-1}$ is investigated in the next section.

It is assumed that the 2-path channel exhibits two echoes with energy content unequal zero, i.e. at least two dominant echoes. This assumption yields the impulse response

$$h[q] = c_1\delta_0[q] + c_2\delta_0[q - q_0] \qquad \text{(Eq.12)}$$

with

c_1, c_2 : complex coefficients representing the path echoes;

q_0 : delay of the second path echo with respect to the first path echo;

δ_0 : Dirac pulse; $\delta_0[k] = 1$ for $k = 0$
$\delta_0[k] = 0$ else

The channel transfer function is obtained by applying a DFT (Eq.9) to Equation 12:

$$H_k = H\left(e^{j\frac{2\pi}{K}k}\right) = c_1 + c_2 \cdot e^{-j\frac{2\pi}{K}kq_0} \tag{Eq.13}$$

With Equation 13 the effective transfer function for differential demodulation along the frequency axis is:

$$\begin{aligned} H_k \cdot H_{k-1}^* &= \left(c_1 + c_2 e^{-j\frac{2\pi}{K}kq_0}\right) \cdot \left(c_1^* + c_2^* e^{+j\frac{2\pi}{K}(k-1)q_0}\right) \\ &= c_a + c_b \cos\left(\frac{\pi}{K} q_0 (2k-1)\right) \end{aligned} \tag{Eq.14}$$

Assuming a noise free 2-path channel, it can be observed from Equation 14 that the symbols on the receiver side are located on a straight line in case the symbol 1+j0 has been send (see above assumption). This straight line can be characterized by a point

$$c_a = |c_1|^2 + |c_2|^2 \cdot e^{-j\frac{2\pi}{K}q_0} \tag{Eq.15}$$

and the vector

$$c_b = 2c_1 c_2^* \cdot e^{-j\frac{\pi}{K}q_0} \tag{Eq.16}$$

which determines its direction.

With the above assumptions, the following geometric derivation can be performed. A more suitable notation for the geometric derivation of the second embodiment of an EPOC algorithm is obtained if the real part of the complex plane is designated as x = Re{z}, the imaginary part as y = Im{z}, respectively, i.e. z = x+jy. With this new notation, the

straight line, on which the received symbols will lie in case of a noise-free two-path channel, is

$$f(x) = a + b \cdot x \qquad \text{(Eq.17)}$$

with

$$a = \mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\} \qquad \text{(Eq.18)}$$

and

$$b = -\frac{\mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\}}{\mathrm{Re}\{c_a\} - \frac{\mathrm{Im}\{c_a\}}{\mathrm{Im}\{c_b\}} \cdot \mathrm{Re}\{c_b\}} \qquad \text{(Eq.19)}$$

Additional noise will spread the symbols around the straight line given by Equations 17 to 19. In this case Equation 19 is the regression curve for the cluster of symbols.

For the geometric derivation of the second embodiment of an EPOC algorithm, the angle φ_K from Equation 11 is chosen to be a function of the square distance of the considered symbol from the origin:

$$\varphi_K = f_K(|z|^2) \qquad \text{(Eq.20)}$$

Equation 20 shows that the complete signal space is distorted (torsion), however, with the distances from the origin being preserved.

For the derivation of the algorithm of the second embodiment, $f_K(\cdot)$ has to be determined such that all decision variables v'_K (assuming no noise) will come to lie on the real axis:

$$\operatorname{Im}\left\{\left(x + jf(x)\right)\cdot e^{j f_k\left(|z|^2\right)}\right\} = 0. \qquad \text{(Eq.21)}$$

Further transformations of Equation 21 lead to a quadratic equation which has to be solved to obtain the solution for φ_k.

In case of a two-path channel, the echo phase offset correction for a given decision variable v_k is

$$v_k' = v_k \cdot e^{j\varphi_k} \qquad \text{(Eq.22)}$$

with

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a + b\sqrt{|v_k|^2\left(1+b^2\right) - a^2}}{-ab + \sqrt{|v_k|^2\left(1+b^2\right) - a^2}}\right) & \text{for } |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for } |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \qquad \text{(Eq.23)}$$

From the two possible solutions of the quadratic equation mentioned above, Equation 23 is the one solution that cannot cause an additional phase shift of 180 degrees.

The two plots in Figure 6 show the projection of the EPOC algorithm of the second embodiment for one quadrant of the complex plane. Depicted here is the quadratic grid in the sector $|\arg(z)| \leq \pi/4$ and the straight line $y = f(x) = a+b\cdot x$ with $a = -1.0$ and $b = 0.5$ (dotted line). In case of a noise-free channel, all received symbols will lie on this straight line if 1+j0 was send. The circle shown in the plots determines the boarder line for the two cases of Equation 23. In the left part, Figure 6 shows the situation before the projection, in the right part, Figure 6 shows the situation after applying the projection algorithm. By looking on the left part, one can see, that the straight line now lies on the real axis with 2+j0 being the fix point of the projection. Therefore, it can be concluded that the

echo phase offset correction algorithm according to the second embodiment fulfills the design goal.

Before the second embodiment of an EPOC algorithm can be applied, the approximation line through the received symbols has to be determined, i.e. the parameters a and b must be estimated. For this purpose, it is assumed that the received symbols lie in sector $|\arg(z)| \leq \pi/4$, if 1+j0 was sent. If symbols other than 1+j0 have been sent, a modulo operation can be applied to project all symbols into the desired sector. Proceeding like this prevents the necessity of deciding on the symbols in an early stage and enables averaging over all signal points of one MCM symbol (instead of averaging over only ¼ of all signal points).

For the following computation rule for the EPOC algorithm of the second embodiment, x_i is used to denote the real part of the i-th signal point and y_i for its imaginary part, respectively (i = 1, 2,..., K). Altogether, K values are available for the determination. By choosing the method of least squares, the straight line which has to be determined can be obtained by minimizing

$$(a,b) = \underset{(\tilde{a},\tilde{b})}{argmin} \sum_{i=1}^{K} \left(y_i - \left(\tilde{a} + \tilde{b} \cdot x_i\right)\right)^2 \qquad \text{(Eq.24)}$$

The solution for Equation 24 can be found in the laid open literature. It is

$$b = \frac{\sum_{i=1}^{K} \left(x_i - \overline{x}\right) \cdot y_i}{\sum_{i=1}^{K} \left(x_i - \overline{x}\right)^2}, \quad a = \overline{y} - \overline{x} \cdot b \qquad \text{(Eq.25)}$$

with mean values

$$\overline{x} = \frac{1}{N} \sum_{i=1}^{K} x_i, \quad \overline{y} = \frac{1}{N} \sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

If necessary, an estimation method with higher robustness

can be applied. However, the trade-off will be a much higher computational complexity.

To avoid problems with the range in which the projection is applicable, the determination of the straight line should be separated into two parts. First, the cluster's centers of gravity are moved onto the axes, following, the signal space is distorted. Assuming that a and b are the original parameters of the straight line and α is the rotation angle, $f_{K(.)}$ has to be applied with the transformed parameters

$$b' = \frac{b \cdot \cos(\alpha) - \sin(\alpha)}{\cos(\alpha) + b \cdot \sin(\alpha)}, \qquad a' = a \cdot \left(\cos(\alpha) - b' \cdot \sin(\alpha)\right) \qquad \text{(Eq.27)}$$

Besides the two EPOC algorithms explained above section, different algorithms can be designed that will, however, most likely exhibit a higher degree of computational complexity.

The new mapping method for Multicarrier Modulation schemes presented herein consists in principal of two important aspects. Differential mapping within one MCM symbol along the frequency axis direction and correction of the channel echo related phase offset on the subcarriers at the receiver side. The advantage of this new mapping scheme is its robustness with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

CLAIMS

1. A method of mapping information onto at least two simultaneous carriers (202, 206, 208) having different frequencies in a multi-carrier modulation system, said method comprising the step of:

   controlling respective parameters of said at least two carriers such that said information is differential encoded.

2. The method according to claim 1, wherein said controlled parameters of said at least two carriers (202, 206, 208) are respective phases and/or amplitudes of said at least two carriers.

3. The method according to claim 1 or 2, wherein said step of controlling respective parameters of said at least two carriers (202, 206, 208) comprises the step of controlling respective parameters of at least two carriers which are adjacent in the frequency axis direction.

4. The method according to one of claims 1 to 3, further comprising the step of controlling the parameter of one of said at least two carriers (206) in order to define an absolute parameter reference.

5. The method according to one of claims 1 to 4, comprising the step of mapping information onto at least three simultaneous carriers which are equally spaced in the frequency axis direction.

6. A method of performing a multi-carrier modulation of a bitstream (102) in a digital broadcasting transmitter (100), said method comprising the steps of:

   phase shift keying (220) said bitstream by associating a

respective phase shift to one or more bits of said bit-stream; and

differential phase encoding said phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and said phase shift, said first and second carriers having different frequencies.

7. The method according to claim 6, wherein the step of differential phase encoding comprises the steps of:

determining (222) the phase of a first carrier based on a phase of a simultaneous second carrier and said phase shift, said first and second carriers having different frequencies;

associating (232) a complex carrier symbol to each phase shift;

assembling (234) a multi-carrier modulation symbol (200) based on said complex carrier symbols; and

performing an inverse Fourier transform (236).

8. The method according to claim 6 or 7, wherein said second carrier is arranged adjacent to said first carrier in the frequency axis direction.

9. The method according to one of claims 6 to 8, wherein said step of phase shift keying (220) said bitstream comprises the step of performing a quadrature phase shift keying using a Gray mapping.

10. The method according to one of claims 6 to 9, comprising the step of controlling the phase of one carrier in order to define an absolute phase reference.

11. The method according to one of claims 6 to 10, comprising the step of controlling the phases of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

12. A method of de-mapping information based on at least two simultaneous encoded carriers having different frequencies in a multi-carrier demodulation system, said method comprising the step of:

recovering said information by differential decoding (142) of respective parameters of said at least two carriers.

13. The method according to claim 12, wherein said step of differential decoding (142) comprises the step of differential decoding respective phases and/or amplitudes of said at least two carriers.

14. The method according to claim 12 or 13, wherein said step of recovering said information comprises the step of decoding respective parameters of at least two carriers which are adjacent in the frequency axis direction.

15. The method according to one of claims 12 to 14, wherein said step of recovering said information comprises the step of decoding respective parameters of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

16. A method of performing a demodulation of a multi-carrier modulated signal in a digital broadcasting system, said method comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

recovering bits of a bitstream from said phase shifts.

17. The method according to claim 16, wherein said step of differential phase decoding comprises the steps of:

performing a Fourier transform (140) to derive a multi-carrier modulated symbol, said multi-carrier modulated symbol comprising complex carrier symbols; and

recovering (142) respective phase shifts from said complex carrier symbols.

18. The method according to claim 16 or 17, wherein said step of differential phase decoding comprises the step of differential phase decoding based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

19. The method according to one of claims 16 to 18, wherein said step of recovering bits of a bitstream from said phase shift comprises the step of demodulating said phase shifts using a Gray de-mapping.

20. The method according to one of claims 16 to 19, wherein said step of differential phase decoding comprises the step of differential phase decoding based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

21. A method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding (142) phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating (500) phase shift uncertainties corresponding to codeable phase shifts from said decoded phase shift;

averaging (520) said echo phase offsets in order to generate an averaged offset; and

correcting (524) each decoded phase shift based on said averaged offset.

22. The method according to claim 21, wherein said step of differential phase decoding comprises the step of differential phase decoding phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

23. The method according to claim 21 or 22, wherein said step of differential phase decoding comprises the step of differential phase decoding phase shifts based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

24. The method according to one of claims 21 to 23, further comprising a step of comparing (516) an absolute value of a symbol associated with a respective decoded phase shift with a threshold, wherein only phase shifts having associated therewith symbols having an absolute value exceeding said threshold are used in said step of averaging said echo phase offsets.

25. A method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a

phase difference between simultaneous carriers having different frequencies, said phase shifts defining signal points in a complex plane;

pre-rotating said signal points into the sector of said complex plane between -45° and +45°;

determining parameters (a, b) of a straight line approximating the location of said pre-rotated signal points in said complex plane;

determining a phase offset based on said parameters (a, b); and

correcting each decoded phase shift based on said phase offset.

26. The method according to claim 25, wherein said simultaneous carriers are equally spaced in the frequency axis direction.

27. The method according to claim 25 or 26, wherein said step of determining said parameters (a, b) comprises a least squares method for selecting those parameters which minimize the deviations of said pre-rotated signal points from said straight line.

28. The method according to claim 27, wherein said parameters (a, b) are determined as follows:

$$b = \frac{\sum_{i=1}^{K}(x_i - \bar{x})\cdot y_i}{\sum_{i=1}^{K}(x_i - \bar{x})^2}, \quad a = \bar{y} - \bar{x}\cdot b \qquad \text{(Eq.25)}$$

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{K} x_i, \quad \bar{y} = \frac{1}{N}\sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

wherein x and y designate the coordinates of the signal points in the complex plane,

i is an index from 1 to N, and

K is the number of signal points.

29. The method according to claim 28, wherein said phase offset (φ_k) is determined as follows:

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a+b\sqrt{|v_k|^2(1+b^2)-a^2}}{-ab+\sqrt{|v_k|^2(1+b^2)-a^2}}\right) & \text{for } |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for } |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \qquad \text{(Eq.23)}$$

wherein v_k is a given decision variable.

30. A mapping device for mapping information onto at least two simultaneous carriers (202, 206, 208) having different frequencies, for a multi-carrier modulation system, said device comprising means for controlling respective parameters of said at least two carriers such that said information is differential encoded.

31. The device according to claim 30, wherein said means for controlling respective parameters of said at least two carriers (202, 206, 208) is adapted to control respective phases and/or amplitudes of said at least two carriers.

32. The device according to claim 30 or 31, wherein said means for controlling respective parameters of said at least two carriers (202, 206, 208) comprises means for controlling respective parameters of at least two carriers which are adjacent in the frequency axis direction.

33. The device according to one of claims 30 to 32, further comprising means for controlling the parameter of one (206) of said at least two carriers such that an absolute parameter reference is defined by said carrier.

34. The device according to one of claims 30 to 33, further comprising means for controlling the parameters of at least three carriers which are equally spaced in the frequency axis direction.

35. A multi-carrier modulator for performing a multi-carrier modulation of a bitstream (102), for a digital broadcasting transmitter (100), said modulator comprising:

means for phase shift keying (220) said bitstream by associating a respective phase shift to one or more bits of said bitstream; and

a differential phase encoder for differential phase encoding said phase shifts by controlling the phase of a first carrier based on a phase of a simultaneous second carrier and said phase shift, said first and second carriers having different frequencies.

36. The modulator according to claim 35, wherein said differential phase encoder comprises:

means (222) for determining the phase of a first carrier based on a phase of a simultaneous second carrier and said phase shift, said first and second carriers having different frequencies;

means (232) for associating a complex carrier symbol to each phase shift;

means (234) for assembling a multi-carrier modulation symbol based on said complex carrier symbols; and

means (236) for performing an inverse Fourier transform.

37. The modulator according to claim 35 or 36, wherein said means (222) for determining said phase of said first carrier is adapted to determine said phase based on a phase of a simultaneous second carrier which is arranged adjacent to said first carrier in the frequency axis direction and said phase shift.

38. The modulator according to one of claims 35 to 37, wherein said means (220) for phase shift keying said bitstream comprises means for performing a quadrature phase shift keying using a Gray mapping.

39. The modulator according to one of claims 35 to 38, comprising means for controlling the phase of one carrier in order to define an absolute phase reference.

40. The modulator according to one of claims 35 to 39, comprising means for controlling the phases of at least three carriers which are equally spaced in the frequency axis direction.

41. A de-mapping device for de-mapping information based on at least two simultaneous encoded carriers having different frequencies, for a multi-carrier demodulation system (130), said de-mapping device (142) comprising:

means for recovering said information by differential decoding of respective parameters of said at least two carriers.

42. The device according to claim 41, wherein said means for recovering said information is adapted to differential decode respective phases and/or amplitudes of said at least two carriers.

43. The device according to claim 41 or 42, wherein said

means for recovering said information comprises means for decoding respective parameters of at least two carriers which are adjacent in the frequency axis direction.

44. The device according to one of claims 41 to 43, wherein said means for recovering said information comprises means for decoding respective parameters of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

45. A demodulator for demodulating a multi-carrier modulated signal, for a digital broadcasting system, said demodulator comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for recovering bits of a bitstream from said phase shifts.

46. The demodulator according to claim 45, wherein said differential phase decoder comprises:

means (140) for performing a Fourier transform to derive a multi-carrier modulated symbol, said multi-carrier modulated symbol comprising complex carrier symbols; and

means (142) for recovering respective phase shifts from said complex carrier symbols.

47. The demodulator according to claim 45 or 46, wherein said differential phase decoder is adapted for decoding phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

48. The demodulator according to one of claims 45 to 47, wherein said means for recovering bits of a bitstream from said phase shift comprises a Gray de-mapper.

49. The demodulator according to one of claims 45 to 48, wherein said simultaneous carriers are equally space in the frequency axis direction.

50. An echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder (142) for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift comprising means (500) for eliminating phase shift uncertainties corresponding to codeable phase shifts from said decoded phase shift;

means (520) for averaging said echo phase offsets in order to generate an averaged offset; and

means (524) for correcting each decoded phase shift based on said averaged offset.

51. The device according to claim 50, wherein said differential phase decoder is adapted for decoding said phase shifts based on a phase difference between simultaneous carriers which are adjacent in the frequency axis direction.

52. The device according to claim 50 or 51, further comprising means (516) for comparing an absolute value of a symbol associated with a respective decoded phase shift with a threshold, wherein said means for averaging said phase offsets only uses phase shifts having associated therewith symbols having an absolute value

exceeding said threshold.

53. The device according to one of claims 50 to 52, wherein said differential phase decoder is adapted for decoding said phase shifts based on phase differences between at least three simultaneous carriers which are equally spaced in the frequency axis direction.

54. An echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, said phase shifts defining signal points in a complex plane;

means for pre-rotating said signal points into the sector of said complex plane between -45° and +45°;

means for determining parameters (a, b) of a straight line approximating the location of said pre-rotated signal points in said complex plane;

means for determining a phase offset based on said parameters (a, b); and

means for correcting each decoded phase shift based on said phase offset.

55. The device according to claim 54, wherein said differential phase decoder comprises means for decoding phase shifts of at least three simultaneous carriers which are equally spaced in the frequency axis direction.

56. The device according to claim 54 or 55, wherein said means for determining said parameters (a, b) comprises means for performing a least squares method for

selecting those parameters which minimize the deviations of said pre-rotated signal points from said straight line.

57. The device according to claim 56, wherein said means for determining said parameters (a, b) calculates said parameters (a, b) as follows:

$$b = \frac{\sum_{i=1}^{K}\left(x_i - \overline{x}\right)\cdot y_i}{\sum_{i=1}^{K}\left(x_i - \overline{x}\right)^2}, \quad a = \overline{y} - \overline{x}\cdot b \qquad \text{(Eq.25)}$$

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{K} x_i, \quad \overline{y} = \frac{1}{N}\sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

wherein x and y designate the coordinates of the signal points in the complex plane,

i is an index from 1 to N, and

K is the number of signal points.

58. The device according to claim 57, wherein said means for determining said phase offset (φ_k) calculates said phase offset (φ_k) as follows:

$$\varphi_k = \begin{cases} -atan\left(\dfrac{a + b\sqrt{|v_k|^2(1+b^2) - a^2}}{-ab + \sqrt{|v_k|^2(1+b^2) - a^2}}\right) & \text{for } |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ atan\left(\dfrac{1}{b}\right) & \text{for } |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \qquad \text{(Eq.23)}$$

wherein v_k is a given decision variable.

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[METHOD AND APPARATUS FOR MULTI-CARRIER MODULATION AND DE-MODULATION AND METHOD AND APPARATUS FOR PERFORMING AN ECHO PHASE OFFSET CORRECTION ASSOCIATED THEREWITH]

ECHO PHASE OFFSET CORRECTION IN A MULTI-CARRIER DEMODULATION SYSTEM

FIELD OF THE INVENTION

The present invention relates to methods and apparatus for performing modulation and de-modulation in multi-carrier modulation systems (MCM systems) and, in particular, to methods and apparatus for differential mapping and de-mapping of information onto carriers of multi-carrier modulation symbols in such systems. Furthermore, the present invention relates to methods and apparatus for performing an echo phase offset correction when decoding information encoded onto carriers of multi-carrier modulation symbols in multi-carrier modulation systems.

BACKGROUND OF THE INVENTION

The present invention generally relates to broadcasting of digital data to mobile receivers over time-variant multipath channels. More specifically, the present invention is particularly useful in multipath environments with low channel coherence time, i.e. rapidly changing channels. In preferred embodiments, the present invention can be applied to systems implementing a multicarrier modulation scheme. Multi-carrier modulation (MCM) is also known as orthogonal frequency division multiplexing (OFDM).

In a MCM transmission system binary information is represented in the form of a complex spectrum, i.e. a distinct number of complex subcarrier symbols in the frequency domain. In the modulator a bitstream is represented by a se-

quence of spectra. Using an inverse Fourier-transform (IFFT) a MCM time domain signal is produced from this sequence of spectra.

Figure 7 shows a MCM system overview. At 100 a MCM transmitter is shown. A description of such a MCM transmitter can be found, for example, in William Y. Zou, Yiyan Wu, "COFDM: AN OVERVIEW", IEEE Transactions on Broadcasting, vol. 41, No. 1, March 1995.

A data source 102 provides a serial bitstream 104 to the MCM transmitter. The incoming serial bitstream 104 is applied to a bit-carrier mapper 106 which produces a sequence of spectra 108 from the incoming serial bitstream 104. An inverse fast Fourier transform (FFT) 110 is performed on the sequence of spectra 108 in order to produce a MCM time domain signal 112. The MCM time domain signal forms the useful MCM symbol of the MCM time signal. To avoid intersymbol interference (ISI) caused by multipath distortion, a unit 114 is provided for inserting a guard interval of fixed length between adjacent MCM symbols in time. In accordance with a preferred embodiment of the present invention, the last part of the useful MCM symbol is used as the guard interval by placing same in front of the useful symbol. The resulting MCM symbol is shown at 115 in Figure 7.

A unit 116 for adding a reference symbol for each predetermined number of MCM symbols is provided in order to produce a MCM signal having a frame structure. Using this frame structure comprising useful symbols, guard intervals and reference symbols it is possible to recover the useful information from the MCM signal at the receiver side.

The resulting MCM signal having the structure shown at 118 in Figure 7 is applied to the transmitter front end 120. Roughly speaking, at the transmitter front end 120, a digital/analog conversion and an up-converting of the MCM signal is performed. Thereafter, the MCM signal is transmitted through a channel 122.

Following, the mode of operation of a MCM receiver 130 is shortly described referring to Figure 7. The MCM signal is received at the receiver front end 132. In the receiver front end 132, the MCM signal is down-converted and, furthermore, a digital/analog conversion of the down-converted signal is performed. The down-converted MCM signal is provided to a frame synchronization unit 134. The frame synchronization unit 134 determines the location of the reference symbol in the MCM symbol. Based on the determination of the frame synchronization unit 134, a reference symbol extracting unit 136 extracts the framing information, i.e. the reference symbol, from the MCM symbol coming from the receiver front end 132. After the extraction of the reference symbol, the MCM signal is applied to a guard interval removal unit 138.

The result of the signal processing performed so far in the MCM receiver are the useful MCM symbols. The useful MCM symbols output from the guard interval removal unit 138 are provided to a fast Fourier transform unit 140 in order to provide a sequence of spectra from the useful symbols. Thereafter, the sequence of spectra is provided to a carrier-bit mapper 142 in which the serial bitstream is recovered. This serial bitstream is provided to a data sink 144.

As it is clear from Figure 7, every MCM transmitter 100 must contain a device which performs mapping of the transmitted bitstreams onto the amplitudes and/or phases of the sub-carriers. In addition, at the MCM receiver 130, a device is needed for the inverse operation, i.e. retrieval of the transmitted bitstream from the amplitudes and/or phases of the sub-carriers.

For a better understanding of MCM mapping schemes, it is preferable to think of the mapping as being the assignment of one ore more bits to one or more sub-carrier symbols in the time-frequency plane. In the following, the term symbol or signal point is used for the complex number which repre-

sents the amplitude and/or phase modulation of a subcarrier in the equivalent baseband. Whenever all complex numbers representing all subcarrier symbols are designated, the term MCM symbol is used.

DESCRIPTION OF PRIOR ART

In principle, two methods for mapping the bitstream into the time-frequency plane are used in the prior art:

A first method is a differential mapping along the time axis. When using differential mapping along the time axis one or more bits are encoded into phase and/or amplitude shifts between two subcarriers of the same center frequency in adjacent MCM symbols. Such an encoding scheme is shown in Figure 8. The arrows depicted between the sub-carrier symbols correspond to information encoded in amplitude and/or phase shifts between two subcarrier symbols.

A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 401 (EU147-DAB). A system compliant to this standard uses Differential Quadrature Phase Shift Keying (DQPSK) to encode every two bits into a 0, 90, 180 or 270 degrees phase difference between two subcarriers of the same center frequency which are located in MCM symbols adjacent in time.

A second method for mapping the bitstream into the time-frequency plane is a non-differential mapping. When using non-differential mapping the information carried on a subcarrier is independent of information transmitted on any other subcarrier, and the other subcarrier may differ either in frequency, i.e. the same MCM symbol, or in time, i.e. adjacent MCM symbols. A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 744 (DVB-T). A system compliant to this standard uses 4,16 or 64 Quadrature Amplitude Modulation (QAM) to assign bits to the amplitude and phase of a subcarrier.

The quality with which transmitted multi-carrier modulated signals can be recovered at the receiver depends on the properties of the channel. The most interesting property when transmitting MCM signals is the time interval at which a mobile channel changes its characteristics considerably. The channel coherence time T_c is normally used to determine the time interval at which a mobile channel changes its characteristics considerably. T_c depends on the maximum Doppler shift as follows:

$$f_{Doppler,\max} = v \cdot f_{carrier} / c \qquad \text{(Eq.1)}$$

with v : speed of the mobile receiver in [m/s]
fcarrier : carrier frequency of the RF signal [Hz]
c : speed of light ($3 \cdot 10^8$ m/s)

The channel coherence time T_c is often defined to be

$$T_c\big|_{50\%} = \frac{9}{16\pi f_{Doppler,\max}} \quad or \quad T_c\big|_{2nd\ Def.} = \frac{9}{16\pi f^2_{Doppler,\max}} \qquad \text{(Eq.2)}$$

It becomes clear from the existence of more than one definition, that the channel coherence time T_c is merely a rule-of-thumb value for the stationarity of the channel. As explained above, the prior art time-axis differential mapping requires that the mobile channel be quasi stationary during several MCM symbols periods, i.e. required channel coherence time Tc >> MCM symbol period. The prior art non-differential MCM mapping only requires that the mobile channel be quasi stationary during one symbol interval, i.e. required channel coherence time ≥ MCM symbol period.

Thus, both prior art mapping schemes have specific disadvantages. For differential mapping into time axis direction the channel must be quasi stationary, i.e. the channel must not change during the transmission of two MCM symbols adjacent

in time. If this requirement is not met, the channel induced phase and amplitude changes between MCM symbols will yield an increase in bit error rate.

With non-differential mapping exact knowledge of the phase of each subcarrier is needed (i.e. coherent reception). For multipath channels, coherent reception can only be obtained if the channel impulse response is known. Therefore, a channel estimation has to be part of the receiver algorithm. The channel estimation usually needs additional sequences in the transmitted waveform which do not carry information. In case of rapidly changing channels, which necessitate update of the channel estimation at short intervals, the additional overhead can quickly lead to insufficiency of non-differential mapping.

P.H. Moose: "Differentially Coded Multi-Frequency Modulation for Digital Communications", SIGNAL PROCESSING THEORIES AND APPLICATIONS, 18. - 21. September 1990, pages 1807 - 1810, Amsterdam, NL, teaches a differentially coded multi-frequency modulation for digital communications. A multi-frequency differential modulation is described in which symbols are differentially encoded within each baud between adjacent tones. At the receiver, following a digital Fourier transform (DFT), the complex product between the DFT coefficient of digital frequency k and the complex conjugate of the DFT coefficient of digital frequency k-1 is formed. Thereafter, the result is multiplied by appropriate terms such that the differentially encoded phase bits are realigned to the original constellations. Thus, the constellation following the differential decoding must correspond to the original constellation.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide methods and devices for performing an echo phase offset correction in a multi-carrier demodulation system.

[This object is achieved by methods according to claims 1 and 5 and devices according to claims 10 and 14.]

In accordance with a first aspect, the present invention provides a method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties related to the transmitted information from the decoded phase shift;

averaging the echo phase offsets in order to generate an averaged offset; and

correcting each decoded phase shift based on the averaged offset.

In accordance with a second aspect, the present invention provides a method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

determining a phase offset based on the parameters; and

correcting each decoded phase shift based on the phase offset.

In accordance with a third aspect, the present invention provides an echo phase offset correction device for a multicarrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties related to the transmitted information from the decoded phase shift;

means for averaging the echo phase offsets in order to generate an averaged offset; and

means for correcting each decoded phase shift based on the averaged offset.

In accordance with a fourth aspect, the present invention provides an echo phase offset correction device for a multicarrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

means for pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

means for determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

means for determining a phase offset based on the parameters; and

means for correcting each decoded phase shift based on the phase offset.

The present invention provides methods and devices for performing an echo phase offset correction, suitable for multicarrier (OFDM) digital broadcasting over rapidly changing multipath channels, [using] comprising differential encoding of the data along the frequency axis such that there is no need for channel stationarity exceeding one multicarrier symbol.

When using the mapping process along the frequency axis it is preferred to make use of a receiver algorithm that will correct symbol phase offsets that can be caused by channel echoes.

The mapping scheme along the frequency axis for multicarrier modulation renders the transmission to a certain extent independent of rapid changes in the multipath channel without introducing a large overhead to support channel estimation. Especially systems with high carrier frequencies and/or high speeds of the mobile carrying the receiving unit can benefit from such a mapping scheme.

Thus, the mapping scheme of a differential encoding along the frequency axis does not exhibit the two problems of the prior art systems described above. The mapping scheme is robust with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

The controlled respective parameters of the subcarriers are the phases thereof, such that the information is differentially phase encoded.

In accordance with the mapping described above, mapping is also differential, however, not into time axis direction but into frequency axis direction. Thus, the information is not contained in the phase shift between subcarriers adjacent in time but in the phase shift between subcarriers adjacent in frequency. Differential mapping along the frequency axis has two advantages when compared to prior art mapping schemes. Because of differential mapping, no estimation of the absolute phase of the subcarriers is required. Therefore, channel estimation and the related overhead are not necessary. By choosing the frequency axis as direction for differentially encoding the information bitstream, the requirement that the channel must be stationary during several MCM symbols can be dropped. The channel only has to remain unchanged during the current MCM symbol period. Therefore, like for non-differential mapping it holds that

required channel coherence time $\geq$ MCM symbol period.

The present invention provides methods and apparatus for correction of phase distortions that can be caused by channel echoes. As described above, differential mapping into frequency axis direction solves problems related to the stationarity of the channel. However, differential mapping into frequency axis direction may create a new problem. In multipath environments, path echoes succeeding or preceding the main path can lead to systematic phase offsets between subcarriers in the same MCM symbol. In this context, the main path is thought of being the path echo with the highest energy content. The main path echo will determine the position of the FFT window in the receiver of an MCM system.

According to the present invention, the information will be contained in a phase shift between adjacent subcarriers of the same MCM symbol. If not corrected for, the path echo induced phase offset between two subcarriers can lead to an increase in bit error rate. Therefore, application of the MCM mapping scheme presented in this invention will preferably be used in combination with a correction of the system-

atic subcarrier phase offsets in case of a multipath channel.

The introduced phase offset can be explained from the shifting property of the Discrete Fourier Transform (DFT):

$$x[((n-m))_N] \xleftrightarrow{DFT} X[k]e^{-j\frac{2\pi}{N}km} \qquad \text{(Eq.3)}$$

with $x[n]$: sampled time domain signal ($0 \le n \le N-1$)
$X[k]$: DFT transformed frequency domain signal ($0 \le k \le N-1$)
N : length of DFT
$(\ldots)_N$: cyclic shift of the DFT window in the time
m : length of DFT-Shift in the time domain

Equation 3 shows, that in a multipath channel, echoes following the main path will yield a subcarrier dependent phase offset. After differential demapping in the frequency axis direction at the receiver, a phase offset between two neighboring symbols remains. Because the channel induced phase offsets between differentially demodulated symbols are systematic errors, they can be corrected by an algorithm.

In the context of the following specification, algorithms which help correcting the phase shift are called Echo Phase Offset Correction (EPOC) algorithms. Two such algorithms are described as preferred embodiments for the correction of phase distortions that can be caused by channel echoes. These algorithms yield a sufficient detection security for MCM frequency axis mapping even in channels with echoes close to the limits of the guard interval.

In principle, an EPOC algorithm must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following, preferred embodiments of the present invention will be explained in detail on the basis of the drawings enclosed, in which:

Figure 1 shows a schematic view representing a mapping scheme used according to the invention;

Figure 2 shows a functional block diagram of an embodiment of a mapping device;

Figures 3A and 3B show scatter diagrams of the output of an differential de-mapper of a MCM receiver for illustrating the effect of an echo phase offset correction;

Figure 4 shows a schematic block diagram for illustrating the position and the functionality of an echo phase offset correction unit;

Figure 5 shows a schematic block diagram of an embodiment of an echo phase offset correction device according to the present invention;

Figure 6 shows schematic views for illustrating a projection performed by another embodiment of an echo phase offset correction device according to the present invention;

Figure 7 shows a schematic block diagram of a generic multi-carrier modulation system; and

Figure 8 shows a schematic view representing a prior art differential mapping scheme.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In a preferred embodiment thereof, the present invention is applied to a MCM system as shown in Figure 7. With respect to this MCM system, the present invention relates to the bit-carrier mapper 106 of the MCM transmitter 100 and the carrier-bit mapper 142 of the MCM receiver 130, which are depicted with a shaded background in Figure 7.

An preferred embodiment of an inventive mapping scheme used by the bit-carrier mapper 106 is depicted in Figure 1. A number of MCM symbols 200 is shown in Figure 1. Each MCM symbol 200 comprises a number of sub-carrier symbols 202. The arrows 204 in Fig. 1 illustrate information encoded between two sub-carrier symbols 202. As can be seen from the arrows 204, the bit-carrier mapper 106 uses a differential mapping within one MCM symbol along the frequency axis direction.

In the embodiment shown in Figure 1, the first sub-carrier (k=0) in an MCM symbol 200 is used as a reference subcarrier 206 (shaded) such that information is encoded between the reference sub-carrier and the first active carrier 208. The other information of a MCM symbol 200 is encoded between active carriers, respectively.

Thus, for every MCM symbol an absolute phase reference exists. In accordance with Figure 1, this absolute phase reference is supplied by a reference symbol inserted into every MCM symbol (k=0). The reference symbol can either have a constant phase for all MCM symbols or a phase that varies from MCM symbol to MCM symbol. A varying phase can be obtained by replicating the phase from the last subcarrier of the MCM symbol preceding in time.

In Figure 2 a preferred embodiment of a device for performing a differential mapping along the frequency axis is shown. Referring to Figure 2, assembly of MCM symbols in the

frequency domain using differential mapping along the frequency axis according to the present invention is described.

Figure 2 shows the assembly of one MCM symbol with the following parameters:

NFFT designates the number of complex coefficients of the discrete Fourier transform, number of subcarriers respectively.

K designates the number of active carriers. The reference carrier is not included in the count for K.

According to Figure 2, a quadrature phase shift keying (QPSK) is used for mapping the bitstream onto the complex symbols. However, other M-ary mapping schemes (MPSK) like 2-PSK, 8-PSK, 16-QAM, 16-APSK, 64-APSK etc. are possible.

Furthermore, for ease of filtering and minimization of aliasing effects some subcarriers are not used for encoding information in the device shown in Figure 2. These subcarriers, which are set to zero, constitute the so-called guard bands on the upper and lower edges of the MCM signal spectrum.

At the input of the mapping device shown in Figure 2, complex signal pairs b0[k], b1[k] of an input bitstream are received. K complex signal pairs are assembled in order to form one MCM symbol. The signal pairs are encoded into the K differential phase shifts phi[k] needed for assembly of one MCM symbol. In this embodiment, mapping from Bits to the 0, 90, 180 and 270 degrees phase shifts is performed using Gray Mapping in a quadrature phase shift keying device 220.

Gray mapping is used to prevent that differential detection phase errors smaller than 135 degrees cause double bit errors at the receiver.

Differential phase encoding of the K phases is performed in a differential phase encoder 222. At this stage of processing, the K phases phi[k] generated by the QPSK Gray mapper are differentially encoded. In principal, a feedback loop 224 calculates a cumulative sum over all K phases. As starting point for the first computation (k = 0) the phase of the reference carrier 226 is used. A switch 228 is provided in order to provide either the absolute phase of the reference subcarrier 226 or the phase information encoded onto the preceding (i.e. z^{-1}, where z^{-1} denotes the unit delay operator) subcarrier to a summing point 230. At the output of the differential phase encoder 222, the phase information theta[k] with which the respective subcarriers are to be encoded is provided. In preferred embodiments of the present invention, the subcarriers of a MCM symbol are equally spaced in the frequency axis direction.

The output of the differential phase encoder 222 is connected to a unit 232 for generating complex subcarrier symbols using the phase information theta[k]. To this end, the K differentially encoded phases are converted to complex symbols by multiplication with

$$\text{factor} * e^{j*[2*pi*(theta[k] + PHI)]} \qquad \text{(Eq.4)}$$

wherein factor designates a scale factor and PHI designates an additional angle. The scale factor and the additional angle PHI are optional. By choosing PHI = 45° a rotated DQPSK signal constellation can be obtained.

Finally, assembly of a MCM symbol is effected in an assembling unit 234. One MCM symbol comprising N_{FFT} subcarriers is assembled from N_{FFT}-K-1 guard band symbols which are "zero", one reference subcarrier symbol and K DQPSK subcarrier symbols. Thus, the assembled MCM symbol 200 is composed of K complex values containing the encoded information, two guard bands at both sides of the NFFT complex values and a reference subcarrier symbol.

The MCM symbol has been assembled in the frequency domain. For transformation into the time domain an inverse discrete Fourier transform (IDFT) of the output of the assembling unit 234 is performed by a transformator 236. In preferred embodiments of the present invention, the transformator 236 is adapted to perform a fast Fourier transform (FFT).

Further processing of the MCM signal in the transmitter as well as in the receiver is as described above referring to Figure 7.

At the receiver a de-mapping device 142 (Figure 7) is needed to reverse the operations of the mapping device described above referring to Figure 2. The implementation of the de-mapping device is straightforward and, therefore, need not be described herein in detail.

However, systematic phase shifts stemming from echoes in multipath environments may occur between subcarriers in the same MCM symbol. This phase offsets can cause bit errors when demodulating the MCM symbol at the receiver.

Thus, it is preferred to make use of an algorithm to correct the systematic phase shifts stemming from echoes in multipath environments. Preferred embodiments of echo phase offset correction algorithms are explained hereinafter referring to Figures 3 to 6.

In Figures 3A and 3B, scatter diagrams at the output of a differential demapper of a MCM receiver are shown. As can be seen from Figure 3A, systematic phase shifts between subcarriers in the same MCM symbol cause a rotation of the demodulated phase shifts with respect to the axis of the complex coordinate system. In Figure 3B, the demodulated phase shifts after having performed an echo phase offset correction are depicted. Now, the positions of the signal points are substantially on the axis of the complex coordinate system. These positions correspond to the modulated phase shifts of 0°, 90°, 180° and 270°, respectively.

An echo phase offset correction algorithm (EPOC algorithm) must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

For illustration purposes, one may think of the simplest algorithm possible which eliminates the symbol phase before computing the mean of all phases of the subcarriers. To illustrate the effect of such an EPOC algorithm, reference is made to the two scatter diagrams of subcarriers symbols contained in one MCM symbol in Figures 3A and 3B. This scatter diagrams have been obtained as result of an MCM simulation. For the simulation a channel has been used which might typically show up in single frequency networks. The echoes of this channel stretched to the limits of the MCM guard interval. The guard interval was chosen to be 25% of the MCM symbol duration in this case.

Figure 4 represents a block diagram for illustrating the position and the functionality of an echo phase offset correction device in a MCM receiver. The signal of a MCM transmitter is transmitted through the channel 122 (Figures 4 and 7) and received at the receiver frontend 132 of the MCM receiver. The signal processing between the receiver frontend and the fast Fourier transformator 140 has been omitted in Figure 4. The output of the fast Fourier transformator is applied to the de-mapper, which performs a differential demapping along the frequency axis. The output of the demapper are the respective phase shifts for the subcarriers. The phase offsets of this phase shifts which are caused by echoes in multipath environments are visualized by a block 400 in Figure 4 which shows an example of a scatter diagram of the subcarrier symbols without an echo phase offset correction.

The output of the de-mapper 142 is applied to the input of an echo phase offset correction device 402. The echo phase offset correction device 402 uses an EPOC algorithm in order

to eliminate echo phase offsets in the output of the de-mapper 142. The result is shown in block 404 of Figure 4, i.e. only the encoded phase shifts, 0°, 90°, 180° or 270° are present at the output of the correction device 402. The output of the correction device 402 forms the signal for the metric calculation which is performed in order to recover the bitstream representing the transmitted information.

A first embodiment of an EPOC algorithm and a device for performing same is now described referring to Figure 5.

The first embodiment of an EPOC algorithm starts from the assumption that every received differentially decoded complex symbol is rotated by an angle due to echoes in the multipath channel. For the subcarriers equal spacing in frequency is assumed since this represents a preferred embodiment of the present invention. If the subcarriers were not equally spaced in frequency, a correction factor would have to be introduced into the EPOC algorithm.

Figure 5 shows the correction device 402 (Figure 4) for performing the first embodiment of an EPOC algorithm.

From the output of the de-mapper 142 which contains an echo phase offset as shown for example in Figure 3A, the phase shifts related to transmitted information must first be discarded. To this end, the output of the de-mapper 142 is applied to a discarding unit 500. In case of a DQPSK mapping, the discarding unit can perform a "$(.)^4$" operation. The unit 500 projects all received symbols into the first quadrant. Therefore, the phase shifts related to transmitted information is eliminated from the phase shifts representing the subcarrier symbols. The same effect could be reached with a modulo-4 operation.

Having eliminated the information related symbol phases in unit 500, the first approach to obtain an estimation would be to simply compute the mean value over all symbol phases of one MCM symbol. However, it is preferred to perform a

threshold decision before determining the mean value over all symbol phases of one MCM symbol. Due to Rayleigh fading some of the received symbols may contribute unreliable information to the determination of the echo phase offset. Therefore, depending on the absolute value of a symbol, a threshold decision is performed in order to determine whether the symbol should contribute to the estimate of the phase offset or not.

Thus, in the embodiment shown in Fig. 5, a threshold decision unit 510 is included. Following the unit 500 the absolute value and the argument of a differentially decoded symbol is computed in respective computing units 512 and 514. Depending on the absolute value of a respective symbol, a control signal is derived. This control signal is compared with a threshold value in a decision circuit 516. If the absolute value, i.e. the control signal thereof, is smaller than a certain threshold, the decision circuit 516 replaces the angle value going into the averaging operation by a value equal to zero. To this end, a switch is provided in order to disconnect the output of the argument computing unit 514 from the input of the further processing stage and connects the input of the further processing stage with a unit 518 providing a constant output of "zero".

An averaging unit 520 is provided in order to calculate a mean value based on the phase offsets φ_i determined for the individual subcarrier symbols of a MCM symbol as follows:

$$\overline{\varphi} = {}^{1}\!/_{K} \sum_{i=1}^{K} \varphi_i \qquad \text{(Eq.5)}$$

In the averaging unit 520, summation over K summands which have not been set to zero in the unit 516 is performed. The output of the averaging unit 520 is provided to a hold unit 522 which holds the output of the averaging unit 520 K times. The output of the hold unit 522 is connected with a phase rotation unit 524 which performs the correction of the

phase offsets of the K complex signal points on the basis of the mean value $\overline{\varphi}$.

The phase rotation unit 524 performs the correction of the phase offsets by making use of the following equation:

$$v_k' = v_k \cdot e^{-j\overline{\varphi}} \qquad \text{(Eq.6)}$$

In this equation, v_k' designates the K phase corrected differentially decoded symbols for input into the soft-metric calculation, whereas v_k designates the input symbols. As long as a channel which is quasi stationary during the duration of one MCM symbols can be assumed, using the mean value over all subcarriers of one MCM symbol will provide correct results.

A buffer unit 527 may be provided in order to buffer the complex signal points until the mean value of the phase offsets for one MCM symbol is determined. The output of the phase rotation unit 524 is applied to the further processing stage 526 for performing the soft-metric calculation.

With respect to the results of the above echo phase offset correction, reference is made again to Figures 3A and 3B. The two plots stem from a simulation which included the first embodiment of an echo phase offset correction algorithm described above. At the instant of the scatter diagram snapshot shown in Figure 3A, the channel obviously distorted the constellation in a way, that a simple angle rotation is a valid assumption. As shown in Figure 3B, the signal constellation can be rotated back to the axis by applying the determined mean value for the rotation of the differentially detected symbols.

A second embodiment of an echo phase offset correction algorithm is described hereinafter. This second embodiment can be preferably used in connection with multipath channels that have up to two strong path echoes. The algorithm of the

second embodiment is more complex than the algorithm of the first embodiment.

What follows is a mathematical derivation of the second embodiment of a method for echo phase offset correction. The following assumptions can be made in order to ease the explanation of the second embodiment of an EPOC algorithm.

In this embodiment, the guard interval of the MCM signal is assumed to be at least as long as the impulse response h[q], q = 0, 1, ..., Qh-1 of the multipath channel.

At the transmitter every MCM symbol is assembled using frequency axis mapping explained above. The symbol of the reference subcarrier equals 1, i.e. 0 degree phase shift. The optional phase shift PHI equals zero, i.e. the DQPSK signal constellation is not rotated.

Using an equation this can be expressed as

$$a_k = a_{k-1} a_k^{inc}$$

(Eq.7)

with

k	:	index k = 1,2,...,K of the active subcarrier;
$a_k^{inc} = e^{j\frac{\pi}{2}m}$	:	complex phase increment symbol; m=0,1,2,3 is the QPSK symbol number which is derived from Gray encoding pairs of 2 Bits;
$a_0 = 1$	:	symbol of the reference subcarrier.

At the DFT output of the receiver the decision variables

$$e_k = a_k H_k \qquad \text{(Eq.8)}$$

are obtained with

$$H_k = \sum_{i=0}^{Q_h-1} h[i] \cdot e^{-j\frac{2\pi}{K}ki} \qquad \text{(Eq.9)}$$

being the DFT of the channel impulse response h[q] at position k.

With $|ak|^2 = 1$ the differential demodulation yields

$$v_k = e_k \cdot e_{k-1}^* = a_k^{inc} H_k H_{k-1}^* \qquad \text{(Eq.10)}$$

For the receiver an additional phase term φ_k is introduced, which shall be used to correct the systematic phase offset caused by the channel. Therefore, the final decision variable at the receiver is

$$v_k^{'} = v_k \cdot e^{j\varphi_k} = a_k^{inc} \cdot e^{j\varphi_k} \cdot H_k \cdot H_{k-1}^* \qquad \text{(Eq.11)}$$

As can be seen from the Equation 11, the useful information a_k^{inc} is weighted with the product $e^{j\varphi_k} \cdot H_k \cdot H_{k-1}^*$ (rotation and effective transfer function of the channel). This product must be real-valued for an error free detection. Considering this, it is best to choose the rotation angle to equal the negative argument of $H_k \cdot H_{k-1}^*$. To derive the desired algorithm for 2-path channels, the nature of $H_k \cdot H_{k-1}^*$ is investigated in the next section.

It is assumed that the 2-path channel exhibits two echoes with energy content unequal zero, i.e. at least two dominant echoes. This assumption yields the impulse response

$$h[q] = c_1\delta_0[q] + c_2\delta_0[q - q_0] \qquad \text{(Eq.12)}$$

with

c_1, c_2 : complex coefficients representing the path echoes;

q_0 : delay of the second path echo with respect to the first path echo;

δ_0 : Dirac pulse; $\delta_0[k] = 1$ for k = 0

$\delta_0[k] = 0$ else

The channel transfer function is obtained by applying a DFT (Eq.9) to Equation 12:

$$H_k = H\left(e^{j\frac{2\pi}{K}k}\right) = c_1 + c_2 \cdot e^{-j\frac{2\pi}{K}kq_0} \qquad \text{(Eq.13)}$$

With Equation 13 the effective transfer function for differential demodulation along the frequency axis is:

$$\begin{aligned} H_k \cdot H_{k-1}^* &= \left(c_1 + c_2 e^{-j\frac{2\pi}{K}kq_0}\right) \cdot \left(c_1^* + c_2^* e^{+j\frac{2\pi}{K}(k-1)q_0}\right) \\ &= c_a + c_b \cos\left(\frac{\pi}{K} q_0 (2k - 1)\right) \qquad \text{(Eq.14)} \end{aligned}$$

Assuming a noise free 2-path channel, it can be observed from Equation 14 that the symbols on the receiver side are located on a straight line in case the symbol 1+j0 has been send (see above assumption). This straight line can be characterized by a point

$$c_a = |c_1|^2 + |c_2|^2 \cdot e^{-j\frac{2\pi}{K}q_0} \qquad \text{(Eq.15)}$$

and the vector

$$c_b = 2c_1c_2^* \cdot e^{-j\frac{\pi}{K}q_0} \qquad \text{(Eq.16)}$$

which determines its direction.

With the above assumptions, the following geometric derivation can be performed. A more suitable notation for the geometric derivation of the second embodiment of an EPOC algo-

rithm is obtained if the real part of the complex plane is designated as x = Re{z}, the imaginary part as y = Im{z}, respectively, i.e. z = x+jy. With this new notation, the straight line, on which the received symbols will lie in case of a noise-free two-path channel, is

$$f(x) = a + b \cdot x \qquad \text{(Eq.17)}$$

with

$$a = \mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\} \qquad \text{(Eq.18)}$$

and

$$b = -\frac{\mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\}}{\mathrm{Re}\{c_a\} - \frac{\mathrm{Im}\{c_a\}}{\mathrm{Im}\{c_b\}} \cdot \mathrm{Re}\{c_b\}} \qquad \text{(Eq.19)}$$

Additional noise will spread the symbols around the straight line given by Equations 17 to 19. In this case Equation 19 is the regression curve for the cluster of symbols.

For the geometric derivation of the second embodiment of an EPOC algorithm, the angle φ_k from Equation 11 is chosen to be a function of the square distance of the considered symbol from the origin:

$$\varphi_k = f_K\left(|z|^2\right) \qquad \text{(Eq.20)}$$

Equation 20 shows that the complete signal space is distorted (torsion), however, with the distances from the origin being preserved.

For the derivation of the algorithm of the second embodiment, $f_K(\cdot)$ has to be determined such that all decision vari-

ables v_k' (assuming no noise) will come to lie on the real axis:

$$\mathrm{Im}\left\{(x + jf(x)) \cdot e^{jf_k(|z|^2)}\right\} = 0 \qquad \text{(Eq.21)}$$

Further transformations of Equation 21 lead to a quadratic equation which has to be solved to obtain the solution for φ_k.

In case of a two-path channel, the echo phase offset correction for a given decision variable v_k is

$$v_k' = v_k \cdot e^{j\varphi_k} \qquad \text{(Eq.22)}$$

with

$$\varphi_k = \begin{cases} -\,a\tan\left(\dfrac{a + b\sqrt{|v_k|^2(1 + b^2) - a^2}}{-\,ab + \sqrt{|v_k|^2(1 + b^2) - a^2}}\right) & \text{for} \quad |v_k|^2 \geq \dfrac{a^2}{1 + b^2} \\ a\tan\left(\dfrac{1}{b}\right) & \text{for} \quad |v_k|^2 < \dfrac{a^2}{1 + b^2} \end{cases}$$

(Eq.23)

From the two possible solutions of the quadratic equation mentioned above, Equation 23 is the one solution that cannot cause an additional phase shift of 180 degrees.

The two plots in Figure 15 show the projection of the EPOC algorithm of the second embodiment for one quadrant of the complex plane. Depicted here is the quadratic grid in the sector $|\arg(z)| \leq \pi / 4$ and the straight line $y = f(x) = a + b \cdot x$ with a = -1.0 and b = 0.5 (dotted line). In case of a noise-free channel, all received symbols will lie on this straight line if 1+j0 was send. The circle shown in the plots determines the boarder line for the two cases of Equation 23. In the left part, Figure 15 shows the situation before the projection, in the right part, Figure 15

shows the situation after applying the projection algorithm. By looking on the left part, one can see, that the straight line now lies on the real axis with 2+j0 being the fix point of the projection. Therefore, it can be concluded that the echo phase offset correction algorithm according to the second embodiment fulfills the design goal.

Before the second embodiment of an EPOC algorithm can be applied, the approximation line through the received symbols has to be determined, i.e. the parameters a and b must be estimated. For this purpose, it is assumed that the received symbols lie in sector $|\arg(z)| \leq \pi / 4$, if 1+j0 was sent. If symbols other than 1+j0 have been sent, a modulo operation can be applied to project all symbols into the desired sector. Proceeding like this prevents the necessity of deciding on the symbols in an early stage and enables averaging over all signal points of one MCM symbol (instead of averaging over only ¼ of all signal points).

For the following computation rule for the EPOC algorithm of the second embodiment, x_i is used to denote the real part of the i-th signal point and y_i for its imaginary part, respectively (i = 1, 2,..., K). Altogether, K values are available for the determination. By choosing the method of least squares, the straight line which has to be determined can be obtained by minimizing

$$(a, b) = \arg\min_{(\tilde{a},\tilde{b})} \sum_{i=1}^{K} \left(y_i - \left(\tilde{a} + \tilde{b} \cdot x_i\right)\right)^2 \qquad \text{(Eq.24)}$$

The solution for Equation 24 can be found in the laid open literature. It is

$$b = \frac{\sum_{i=1}^{K} (x_i - \overline{x}) \cdot y_i}{\sum_{i=1}^{K} (x_i - \overline{x})^2}, \quad a = \overline{y} - \overline{x} \cdot b \qquad \text{(Eq.25)}$$

with mean values

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{K} x_i, \qquad \overline{y} = \frac{1}{N}\sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

If necessary, an estimation method with higher robustness can be applied. However, the trade-off will be a much higher computational complexity.

To avoid problems with the range in which the projection is applicable, the determination of the straight line should be separated into two parts. First, the cluster's centers of gravity are moved onto the axes, following, the signal space is distorted. Assuming that a and b are the original parameters of the straight line and α is the rotation angle, $f_K(\cdot)$ has to be applied with the transformed parameters

$$b' = \frac{b \cdot \cos(\alpha) - \sin(\alpha)}{\cos(\alpha) + b \cdot \sin(\alpha)}, \qquad a' = a \cdot \left(\cos(\alpha) - b' \cdot \sin(\alpha)\right)$$

(Eq.27)

Besides the two EPOC algorithms explained above section, different algorithms can be designed that will, however, most likely exhibit a higher degree of computational complexity.

The new mapping method for Multicarrier Modulation schemes presented herein consists in principal of two important aspects. Differential mapping within one MCM symbol along the frequency axis direction and correction of the channel echo related phase offset on the subcarriers at the receiver side. The advantage of this new mapping scheme is its robustness with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

[METHOD AND APPARATUS FOR MULTI-CARRIER MODULATION AND DE-MODULATION AND METHOD AND APPARATUS FOR PERFORMING AN ECHO PHASE OFFSET CORRECTION ASSOCIATED THEREWITH]

ABSTRACT

A method of [mapping information onto at least two simultaneous carriers (202, 206, 208) having different frequencies] performing an echo phase offset correction in a multi-carrier [modulation] demodulation system involves the step of [controlling respective parameters of that at least two carriers such that the information is differential encoded. A method of demapping information based on at least two simultaneous encoded carriers having different frequencies in a multi-carrier demodulation system comprises the step of recovering the information by] differential phase decoding [(142) of respective parameters of the at least two carriers. In a method of performing an echo phase offset correction in a multi-carrier demodulation system,] phase shifts [are differential phase decoded (142)] based on a phase difference between simultaneous carriers having different frequencies. An echo phase offset is determined for each decoded phase shift by eliminating [(500)] phase shift uncertainties [corresponding to codeable phase shifts] related to the transmitted information from the decoded phase shift. The echo phase offsets are averaged [(520)] in order to generate an averaged offset. Finally, each decoded phase shift is corrected [(524)] based on the averaged offset.

ECHO PHASE OFFSET CORRECTION IN A MULTI-CARRIER DEMODULATION SYSTEM

FIELD OF THE INVENTION

The present invention relates to methods and apparatus for performing modulation and de-modulation in multi-carrier modulation systems (MCM systems) and, in particular, to methods and apparatus for differential mapping and de-mapping of information onto carriers of multi-carrier modulation symbols in such systems. Furthermore, the present invention relates to methods and apparatus for performing an echo phase offset correction when decoding information encoded onto carriers of multi-carrier modulation symbols in multi-carrier modulation systems.

BACKGROUND OF THE INVENTION

The present invention generally relates to broadcasting of digital data to mobile receivers over time-variant multipath channels. More specifically, the present invention is particularly useful in multipath environments with low channel coherence time, i.e. rapidly changing channels. In preferred embodiments, the present invention can be applied to systems implementing a multicarrier modulation scheme. Multi-carrier modulation (MCM) is also known as orthogonal frequency division multiplexing (OFDM).

In a MCM transmission system binary information is represented in the form of a complex spectrum, i.e. a distinct number of complex subcarrier symbols in the frequency domain. In the modulator a bitstream is represented by a sequence of spectra. Using an inverse Fourier-transform (IFFT) a MCM time domain signal is produced from this sequence of spectra.

Figure 7 shows a MCM system overview. At 100 a MCM transmitter is shown. A description of such a MCM transmitter can be found, for example, in William Y. Zou, Yiyan Wu, "COFDM: AN OVERVIEW", IEEE Transactions on Broadcasting, vol. 41, No. 1, March 1995.

A data source 102 provides a serial bitstream 104 to the MCM transmitter. The incoming serial bitstream 104 is applied to a bit-carrier mapper 106 which produces a sequence of spectra 108 from the incoming serial bitstream 104. An inverse fast Fourier transform (FFT) 110 is performed on the sequence of spectra 108 in order to produce a MCM time domain signal 112. The MCM time domain signal forms the useful MCM symbol of the MCM time signal. To avoid intersymbol interference (ISI) caused by multipath distortion, a unit 114 is provided for inserting a guard interval of fixed length between adjacent MCM symbols in time. In accordance with a preferred embodiment of the present invention, the last part of the useful MCM symbol is used as the guard interval by placing same in front of the useful symbol. The resulting MCM symbol is shown at 115 in Figure 7.

A unit 116 for adding a reference symbol for each predetermined number of MCM symbols is provided in order to produce a MCM signal having a frame structure. Using this frame structure comprising useful symbols, guard intervals and reference symbols it is possible to recover the useful information from the MCM signal at the receiver side.

The resulting MCM signal having the structure shown at 118 in Figure 7 is applied to the transmitter front end 120. Roughly speaking, at the transmitter front end 120, a digital/analog conversion and an up-converting of the MCM signal is performed. Thereafter, the MCM signal is transmitted through a channel 122.

Following, the mode of operation of a MCM receiver 130 is shortly described referring to Figure 7. The MCM signal is received at the receiver front end 132. In the receiver

front end 132, the MCM signal is down-converted and, furthermore, a digital/analog conversion of the down-converted signal is performed. The down-converted MCM signal is provided to a frame synchronization unit 134. The frame synchronization unit 134 determines the location of the reference symbol in the MCM symbol. Based on the determination of the frame synchronization unit 134, a reference symbol extracting unit 136 extracts the framing information, i.e. the reference symbol, from the MCM symbol coming from the receiver front end 132. After the extraction of the reference symbol, the MCM signal is applied to a guard interval removal unit 138.

The result of the signal processing performed so far in the MCM receiver are the useful MCM symbols. The useful MCM symbols output from the guard interval removal unit 138 are provided to a fast Fourier transform unit 140 in order to provide a sequence of spectra from the useful symbols. Thereafter, the sequence of spectra is provided to a carrier-bit mapper 142 in which the serial bitstream is recovered. This serial bitstream is provided to a data sink 144.

As it is clear from Figure 7, every MCM transmitter 100 must contain a device which performs mapping of the transmitted bitstreams onto the amplitudes and/or phases of the sub-carriers. In addition, at the MCM receiver 130, a device is needed for the inverse operation, i.e. retrieval of the transmitted bitstream from the amplitudes and/or phases of the sub-carriers.

For a better understanding of MCM mapping schemes, it is preferable to think of the mapping as being the assignment of one ore more bits to one or more sub-carrier symbols in the time-frequency plane. In the following, the term symbol or signal point is used for the complex number which represents the amplitude and/or phase modulation of a subcarrier in the equivalent baseband. Whenever all complex numbers representing all subcarrier symbols are designated, the term MCM symbol is used.

DESCRIPTION OF PRIOR ART

In principle, two methods for mapping the bitstream into the time-frequency plane are used in the prior art:

A first method is a differential mapping along the time axis. When using differential mapping along the time axis one or more bits are encoded into phase and/or amplitude shifts between two subcarriers of the same center frequency in adjacent MCM symbols. Such an encoding scheme is shown in Figure 8. The arrows depicted between the sub-carrier symbols correspond to information encoded in amplitude and/or phase shifts between two subcarrier symbols.

A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 401 (EU147-DAB). A system compliant to this standard uses Differential Quadrature Phase Shift Keying (DQPSK) to encode every two bits into a 0, 90, 180 or 270 degrees phase difference between two subcarriers of the same center frequency which are located in MCM symbols adjacent in time.

A second method for mapping the bitstream into the time-frequency plane is a non-differential mapping. When using non-differential mapping the information carried on a subcarrier is independent of information transmitted on any other subcarrier, and the other subcarrier may differ either in frequency, i.e. the same MCM symbol, or in time, i.e. adjacent MCM symbols. A system applying such a mapping scheme is defined in the European Telecommunication Standard ETS 300 744 (DVB-T). A system compliant to this standard uses 4,16 or 64 Quadrature Amplitude Modulation (QAM) to assign bits to the amplitude and phase of a subcarrier.

The quality with which transmitted multi-carrier modulated signals can be recovered at the receiver depends on the properties of the channel. The most interesting property

when transmitting MCM signals is the time interval at which a mobile channel changes its characteristics considerably. The channel coherence time T_c is normally used to determine the time interval at which a mobile channel changes its characteristics considerably. T_c depends on the maximum Doppler shift as follows:

$$f_{Doppler,\max} = v \cdot f_{carrier} / c \qquad \text{(Eq.1)}$$

with v : speed of the mobile receiver in [m/s]
fcarrier : carrier frequency of the RF signal [Hz]
c : speed of light ($3 \cdot 10^8$ m/s)

The channel coherence time T_c is often defined to be

$$T_c\big|_{50\%} = \frac{9}{16\pi f_{Doppler,\max}} \quad or \quad T_c\big|_{2nd\ Def.} = \frac{9}{16\pi f^2_{Doppler,\max}} \qquad \text{(Eq.2)}$$

It becomes clear from the existence of more than one definition, that the channel coherence time T_c is merely a rule-of-thumb value for the stationarity of the channel. As explained above, the prior art time-axis differential mapping requires that the mobile channel be quasi stationary during several MCM symbols periods, i.e. required channel coherence time Tc >> MCM symbol period. The prior art non-differential MCM mapping only requires that the mobile channel be quasi stationary during one symbol interval, i.e. required channel coherence time ≥ MCM symbol period.

Thus, both prior art mapping schemes have specific disadvantages. For differential mapping into time axis direction the channel must be quasi stationary, i.e. the channel must not change during the transmission of two MCM symbols adjacent in time. If this requirement is not met, the channel induced phase and amplitude changes between MCM symbols will yield an increase in bit error rate.

With non-differential mapping exact knowledge of the phase of each subcarrier is needed (i.e. coherent reception). For multipath channels, coherent reception can only be obtained if the channel impulse response is known. Therefore, a channel estimation has to be part of the receiver algorithm. The channel estimation usually needs additional sequences in the transmitted waveform which do not carry information. In case of rapidly changing channels, which necessitate update of the channel estimation at short intervals, the additional overhead can quickly lead to insufficiency of non-differential mapping.

P.H. Moose: "Differentially Coded Multi-Frequency Modulation for Digital Communications", SIGNAL PROCESSING THEORIES AND APPLICATIONS, 18. - 21. September 1990, pages 1807 - 1810, Amsterdam, NL, teaches a differentially coded multi-frequency modulation for digital communications. A multi-frequency differential modulation is described in which symbols are differentially encoded within each baud between adjacent tones. At the receiver, following a digital Fourier transform (DFT), the complex product between the DFT coefficient of digital frequency k and the complex conjugate of the DFT coefficient of digital frequency k-1 is formed. Thereafter, the result is multiplied by appropriate terms such that the differentially encoded phase bits are realigned to the original constellations. Thus, the constellation following the differential decoding must correspond to the original constellation.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide methods and devices for performing an echo phase offset correction in a multi-carrier demodulation system.

In accordance with a first aspect, the present invention provides a method of performing an echo phase offset correc-

tion in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties related to the transmitted information from the decoded phase shift;

averaging the echo phase offsets in order to generate an averaged offset; and

correcting each decoded phase shift based on the averaged offset.

In accordance with a second aspect, the present invention provides a method of performing an echo phase offset correction in a multi-carrier demodulation system, comprising the steps of:

differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

determining a phase offset based on the parameters; and

correcting each decoded phase shift based on the phase offset.

In accordance with a third aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies;

means for determining an echo phase offset for each decoded phase shift by eliminating phase shift uncertainties related to the transmitted information from the decoded phase shift;

means for averaging the echo phase offsets in order to generate an averaged offset; and

means for correcting each decoded phase shift based on the averaged offset.

In accordance with a fourth aspect, the present invention provides an echo phase offset correction device for a multi-carrier demodulation system, comprising:

a differential phase decoder for decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies, the phase shifts defining signal points in a complex plane;

means for pre-rotating the signal points into the sector of the complex plane between -45° and +45°;

means for determining parameters of a straight line approximating the location of the pre-rotated signal points in the complex plane;

means for determining a phase offset based on the parameters; and

means for correcting each decoded phase shift based on the phase offset.

The present invention provides methods and devices for performing an echo phase offset correction, suitable for multicarrier (OFDM) digital broadcasting over rapidly changing multipath channels, comprising differential encoding of the data along the frequency axis such that there is no need for channel stationarity exceeding one multicarrier symbol.

When using the mapping process along the frequency axis it is preferred to make use of a receiver algorithm that will correct symbol phase offsets that can be caused by channel echoes.

The mapping scheme along the frequency axis for multicarrier modulation renders the transmission to a certain extent independent of rapid changes in the multipath channel without introducing a large overhead to support channel estimation. Especially systems with high carrier frequencies and/or high speeds of the mobile carrying the receiving unit can benefit from such a mapping scheme.

Thus, the mapping scheme of a differential encoding along the frequency axis does not exhibit the two problems of the prior art systems described above. The mapping scheme is robust with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

The controlled respective parameters of the subcarriers are the phases thereof, such that the information is differentially phase encoded.

In accordance with the mapping described above, mapping is also differential, however, not into time axis direction but into frequency axis direction. Thus, the information is not contained in the phase shift between subcarriers adjacent in time but in the phase shift between subcarriers adjacent in frequency. Differential mapping along the frequency axis has two advantages when compared to prior art mapping schemes.

Because of differential mapping, no estimation of the absolute phase of the subcarriers is required. Therefore, channel estimation and the related overhead are not necessary. By choosing the frequency axis as direction for differentially encoding the information bitstream, the requirement that the channel must be stationary during several MCM symbols can be dropped. The channel only has to remain unchanged during the current MCM symbol period. Therefore, like for non-differential mapping it holds that

required channel coherence time $\geq$ MCM symbol period.

The present invention provides methods and apparatus for correction of phase distortions that can be caused by channel echoes. As described above, differential mapping into frequency axis direction solves problems related to the stationarity of the channel. However, differential mapping into frequency axis direction may create a new problem. In multipath environments, path echoes succeeding or preceding the main path can lead to systematic phase offsets between subcarriers in the same MCM symbol. In this context, the main path is thought of being the path echo with the highest energy content. The main path echo will determine the position of the FFT window in the receiver of an MCM system.

According to the present invention, the information will be contained in a phase shift between adjacent subcarriers of the same MCM symbol. If not corrected for, the path echo induced phase offset between two subcarriers can lead to an increase in bit error rate. Therefore, application of the MCM mapping scheme presented in this invention will preferably be used in combination with a correction of the systematic subcarrier phase offsets in case of a multipath channel.

The introduced phase offset can be explained from the shifting property of the Discrete Fourier Transform (DFT):

$$x\left[((n-m))_N\right] \xleftrightarrow{\text{DFT}} X[k]e^{-j\frac{2\pi}{N}km} \qquad \text{(Eq.3)}$$

with $x[n]$: sampled time domain signal ($0 \le n \le N-1$)
$X[k]$: DFT transformed frequency domain signal ($0 \le k \le N-1$)
N : length of DFT
$(\ldots)_N$: cyclic shift of the DFT window in the time
m : length of DFT-Shift in the time domain

Equation 3 shows, that in a multipath channel, echoes following the main path will yield a subcarrier dependent phase offset. After differential demapping in the frequency axis direction at the receiver, a phase offset between two neighboring symbols remains. Because the channel induced phase offsets between differentially demodulated symbols are systematic errors, they can be corrected by an algorithm.

In the context of the following specification, algorithms which help correcting the phase shift are called Echo Phase Offset Correction (EPOC) algorithms. Two such algorithms are described as preferred embodiments for the correction of phase distortions that can be caused by channel echoes. These algorithms yield a sufficient detection security for MCM frequency axis mapping even in channels with echoes close to the limits of the guard interval.

In principle, an EPOC algorithm must calculate the echo induced phase offset from the signal space constellation following the differential demodulation and subsequently correct this phase offset.

BRIEF DESCRIPTION OF THE DRAWINGS

In the following, preferred embodiments of the present invention will be explained in detail on the basis of the drawings enclosed, in which:

Figure 1 shows a schematic view representing a mapping scheme used according to the invention;

Figure 2 shows a functional block diagram of an embodiment of a mapping device;

Figures 3A and 3B show scatter diagrams of the output of an differential de-mapper of a MCM receiver for illustrating the effect of an echo phase offset correction;

Figure 4 shows a schematic block diagram for illustrating the position and the functionality of an echo phase offset correction unit;

Figure 5 shows a schematic block diagram of an embodiment of an echo phase offset correction device according to the present invention;

Figure 6 shows schematic views for illustrating a projection performed by another embodiment of an echo phase offset correction device according to the present invention;

Figure 7 shows a schematic block diagram of a generic multi-carrier modulation system; and

Figure 8 shows a schematic view representing a prior art differential mapping scheme.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In a preferred embodiment thereof, the present invention is applied to a MCM system as shown in Figure 7. With respect

to this MCM system, the present invention relates to the bit-carrier mapper 106 of the MCM transmitter 100 and the carrier-bit mapper 142 of the MCM receiver 130, which are depicted with a shaded background in Figure 7.

An preferred embodiment of an inventive mapping scheme used by the bit-carrier mapper 106 is depicted in Figure 1. A number of MCM symbols 200 is shown in Figure 1. Each MCM symbol 200 comprises a number of sub-carrier symbols 202. The arrows 204 in Fig. 1 illustrate information encoded between two sub-carrier symbols 202. As can be seen from the arrows 204, the bit-carrier mapper 106 uses a differential mapping within one MCM symbol along the frequency axis direction.

In the embodiment shown in Figure 1, the first sub-carrier (k=0) in an MCM symbol 200 is used as a reference subcarrier 206 (shaded) such that information is encoded between the reference sub-carrier and the first active carrier 208. The other information of a MCM symbol 200 is encoded between active carriers, respectively.

Thus, for every MCM symbol an absolute phase reference exists. In accordance with Figure 1, this absolute phase reference is supplied by a reference symbol inserted into every MCM symbol (k=0). The reference symbol can either have a constant phase for all MCM symbols or a phase that varies from MCM symbol to MCM symbol. A varying phase can be obtained by replicating the phase from the last subcarrier of the MCM symbol preceding in time.

In Figure 2 a preferred embodiment of a device for performing a differential mapping along the frequency axis is shown. Referring to Figure 2, assembly of MCM symbols in the frequency domain using differential mapping along the frequency axis according to the present invention is described.

Figure 2 shows the assembly of one MCM symbol with the following parameters:

NFFT designates the number of complex coefficients of the discrete Fourier transform, number of subcarriers respectively.

K designates the number of active carriers. The reference carrier is not included in the count for K.

According to Figure 2, a quadrature phase shift keying (QPSK) is used for mapping the bitstream onto the complex symbols. However, other M-ary mapping schemes (MPSK) like 2-PSK, 8-PSK, 16-QAM, 16-APSK, 64-APSK etc. are possible.

Furthermore, for ease of filtering and minimization of aliasing effects some subcarriers are not used for encoding information in the device shown in Figure 2. These subcarriers, which are set to zero, constitute the so-called guard bands on the upper and lower edges of the MCM signal spectrum.

At the input of the mapping device shown in Figure 2, complex signal pairs b0[k], b1[k] of an input bitstream are received. K complex signal pairs are assembled in order to form one MCM symbol. The signal pairs are encoded into the K differential phase shifts phi[k] needed for assembly of one MCM symbol. In this embodiment, mapping from Bits to the 0, 90, 180 and 270 degrees phase shifts is performed using Gray Mapping in a quadrature phase shift keying device 220.

Gray mapping is used to prevent that differential detection phase errors smaller than 135 degrees cause double bit errors at the receiver.

Differential phase encoding of the K phases is performed in a differential phase encoder 222. At this stage of processing, the K phases phi[k] generated by the QPSK Gray mapper are differentially encoded. In principal, a feedback loop 224 calculates a cumulative sum over all K phases. As start-

ing point for the first computation (k = 0) the phase of the reference carrier 226 is used. A switch 228 is provided in order to provide either the absolute phase of the reference subcarrier 226 or the phase information encoded onto the preceding (i.e. z^{-1}, where z^{-1} denotes the unit delay operator) subcarrier to a summing point 230. At the output of the differential phase encoder 222, the phase information theta[k] with which the respective subcarriers are to be encoded is provided. In preferred embodiments of the present invention, the subcarriers of a MCM symbol are equally spaced in the frequency axis direction.

The output of the differential phase encoder 222 is connected to a unit 232 for generating complex subcarrier symbols using the phase information theta[k]. To this end, the K differentially encoded phases are converted to complex symbols by multiplication with

$$\text{factor} * e^{j*[2*pi*(theta[k] + PHI)]} \qquad \text{(Eq.4)}$$

wherein factor designates a scale factor and PHI designates an additional angle. The scale factor and the additional angle PHI are optional. By choosing PHI = 45° a rotated DQPSK signal constellation can be obtained.

Finally, assembly of a MCM symbol is effected in an assembling unit 234. One MCM symbol comprising N_{FFT} subcarriers is assembled from N_{FFT}-K-1 guard band symbols which are "zero", one reference subcarrier symbol and K DQPSK subcarrier symbols. Thus, the assembled MCM symbol 200 is composed of K complex values containing the encoded information, two guard bands at both sides of the NFFT complex values and a reference subcarrier symbol.

The MCM symbol has been assembled in the frequency domain. For transformation into the time domain an inverse discrete Fourier transform (IDFT) of the output of the assembling unit 234 is performed by a transformator 236. In preferred

embodiments of the present invention, the transformator 236 is adapted to perform a fast Fourier transform (FFT).

Further processing of the MCM signal in the transmitter as well as in the receiver is as described above referring to Figure 7.

At the receiver a de-mapping device 142 (Figure 7) is needed to reverse the operations of the mapping device described above referring to Figure 2. The implementation of the de-mapping device is straightforward and, therefore, need not be described herein in detail.

However, systematic phase shifts stemming from echoes in multipath environments may occur between subcarriers in the same MCM symbol. This phase offsets can cause bit errors when demodulating the MCM symbol at the receiver.

Thus, it is preferred to make use of an algorithm to correct the systematic phase shifts stemming from echoes in multipath environments. Preferred embodiments of echo phase offset correction algorithms are explained hereinafter referring to Figures 3 to 6.

In Figures 3A and 3B, scatter diagrams at the output of a differential demapper of a MCM receiver are shown. As can be seen from Figure 3A, systematic phase shifts between subcarriers in the same MCM symbol cause a rotation of the demodulated phase shifts with respect to the axis of the complex coordinate system. In Figure 3B, the demodulated phase shifts after having performed an echo phase offset correction are depicted. Now, the positions of the signal points are substantially on the axis of the complex coordinate system. These positions correspond to the modulated phase shifts of 0°, 90°, 180° and 270°, respectively.

An echo phase offset correction algorithm (EPOC algorithm) must calculate the echo induced phase offset from the signal

space constellation following the differential demodulation and subsequently correct this phase offset.

For illustration purposes, one may think of the simplest algorithm possible which eliminates the symbol phase before computing the mean of all phases of the subcarriers. To illustrate the effect of such an EPOC algorithm, reference is made to the two scatter diagrams of subcarriers symbols contained in one MCM symbol in Figures 3A and 3B. This scatter diagrams have been obtained as result of an MCM simulation. For the simulation a channel has been used which might typically show up in single frequency networks. The echoes of this channel stretched to the limits of the MCM guard interval. The guard interval was chosen to be 25% of the MCM symbol duration in this case.

Figure 4 represents a block diagram for illustrating the position and the functionality of an echo phase offset correction device in a MCM receiver. The signal of a MCM transmitter is transmitted through the channel 122 (Figures 4 and 7) and received at the receiver frontend 132 of the MCM receiver. The signal processing between the receiver frontend and the fast Fourier transformator 140 has been omitted in Figure 4. The output of the fast Fourier transformator is applied to the de-mapper, which performs a differential demapping along the frequency axis. The output of the demapper are the respective phase shifts for the subcarriers. The phase offsets of this phase shifts which are caused by echoes in multipath environments are visualized by a block 400 in Figure 4 which shows an example of a scatter diagram of the subcarrier symbols without an echo phase offset correction.

The output of the de-mapper 142 is applied to the input of an echo phase offset correction device 402. The echo phase offset correction device 402 uses an EPOC algorithm in order to eliminate echo phase offsets in the output of the demapper 142. The result is shown in block 404 of Figure 4, i.e. only the encoded phase shifts, 0°, 90°, 180° or 270°

are present at the output of the correction device 402. The output of the correction device 402 forms the signal for the metric calculation which is performed in order to recover the bitstream representing the transmitted information.

A first embodiment of an EPOC algorithm and a device for performing same is now described referring to Figure 5.

The first embodiment of an EPOC algorithm starts from the assumption that every received differentially decoded complex symbol is rotated by an angle due to echoes in the multipath channel. For the subcarriers equal spacing in frequency is assumed since this represents a preferred embodiment of the present invention. If the subcarriers were not equally spaced in frequency, a correction factor would have to be introduced into the EPOC algorithm.

Figure 5 shows the correction device 402 (Figure 4) for performing the first embodiment of an EPOC algorithm.

From the output of the de-mapper 142 which contains an echo phase offset as shown for example in Figure 3A, the phase shifts related to transmitted information must first be discarded. To this end, the output of the de-mapper 142 is applied to a discarding unit 500. In case of a DQPSK mapping, the discarding unit can perform a "$(.)^4$" operation. The unit 500 projects all received symbols into the first quadrant. Therefore, the phase shifts related to transmitted information is eliminated from the phase shifts representing the subcarrier symbols. The same effect could be reached with a modulo-4 operation.

Having eliminated the information related symbol phases in unit 500, the first approach to obtain an estimation would be to simply compute the mean value over all symbol phases of one MCM symbol. However, it is preferred to perform a threshold decision before determining the mean value over all symbol phases of one MCM symbol. Due to Rayleigh fading some of the received symbols may contribute unreliable in-

formation to the determination of the echo phase offset. Therefore, depending on the absolute value of a symbol, a threshold decision is performed in order to determine whether the symbol should contribute to the estimate of the phase offset or not.

Thus, in the embodiment shown in Fig. 5, a threshold decision unit 510 is included. Following the unit 500 the absolute value and the argument of a differentially decoded symbol is computed in respective computing units 512 and 514. Depending on the absolute value of a respective symbol, a control signal is derived. This control signal is compared with a threshold value in a decision circuit 516. If the absolute value, i.e. the control signal thereof, is smaller than a certain threshold, the decision circuit 516 replaces the angle value going into the averaging operation by a value equal to zero. To this end, a switch is provided in order to disconnect the output of the argument computing unit 514 from the input of the further processing stage and connects the input of the further processing stage with a unit 518 providing a constant output of "zero".

An averaging unit 520 is provided in order to calculate a mean value based on the phase offsets φ_i determined for the individual subcarrier symbols of a MCM symbol as follows:

$$\overline{\varphi} = \frac{1}{K} \sum_{i=1}^{K} \varphi_i \qquad \text{(Eq.5)}$$

In the averaging unit 520, summation over K summands which have not been set to zero in the unit 516 is performed. The output of the averaging unit 520 is provided to a hold unit 522 which holds the output of the averaging unit 520 K times. The output of the hold unit 522 is connected with a phase rotation unit 524 which performs the correction of the phase offsets of the K complex signal points on the basis of the mean value $\overline{\varphi}$.

The phase rotation unit 524 performs the correction of the phase offsets by making use of the following equation:

$$v'_k = v_k \cdot e^{-j\bar{\varphi}} \qquad \text{(Eq.6)}$$

In this equation, v'_k designates the K phase corrected differentially decoded symbols for input into the soft-metric calculation, whereas v_k designates the input symbols. As long as a channel which is quasi stationary during the duration of one MCM symbols can be assumed, using the mean value over all subcarriers of one MCM symbol will provide correct results.

A buffer unit 527 may be provided in order to buffer the complex signal points until the mean value of the phase offsets for one MCM symbol is determined. The output of the phase rotation unit 524 is applied to the further processing stage 526 for performing the soft-metric calculation.

With respect to the results of the above echo phase offset correction, reference is made again to Figures 3A and 3B. The two plots stem from a simulation which included the first embodiment of an echo phase offset correction algorithm described above. At the instant of the scatter diagram snapshot shown in Figure 3A, the channel obviously distorted the constellation in a way, that a simple angle rotation is a valid assumption. As shown in Figure 3B, the signal constellation can be rotated back to the axis by applying the determined mean value for the rotation of the differentially detected symbols.

A second embodiment of an echo phase offset correction algorithm is described hereinafter. This second embodiment can be preferably used in connection with multipath channels that have up to two strong path echoes. The algorithm of the second embodiment is more complex than the algorithm of the first embodiment.

What follows is a mathematical derivation of the second embodiment of a method for echo phase offset correction. The following assumptions can be made in order to ease the explanation of the second embodiment of an EPOC algorithm.

In this embodiment, the guard interval of the MCM signal is assumed to be at least as long as the impulse response h[q], q = 0, 1, ..., Qh-1 of the multipath channel.

At the transmitter every MCM symbol is assembled using frequency axis mapping explained above. The symbol of the reference subcarrier equals 1, i.e. 0 degree phase shift. The optional phase shift PHI equals zero, i.e. the DQPSK signal constellation is not rotated.

Using an equation this can be expressed as

$$a_k = a_{k-1} a_k^{inc}$$
(Eq.7)

with

k	:	index k = 1,2,...,K of the active subcarrier;
$a_k^{inc} = e^{j\frac{\pi}{2}m}$	:	complex phase increment symbol; m=0,1,2,3 is the QPSK symbol number which is derived from Gray encoding pairs of 2 Bits;
$a_0 = 1$	:	symbol of the reference subcarrier.

At the DFT output of the receiver the decision variables

$$e_k = a_k H_k \qquad \text{(Eq.8)}$$

are obtained with

$$H_k = \sum_{i=0}^{Q_h-1} h[i] \cdot e^{-j\frac{2\pi}{K}ki} \qquad \text{(Eq.9)}$$

being the DFT of the channel impulse response h[q] at position k.

With $|ak|^2 = 1$ the differential demodulation yields

$$v_k = e_k \cdot e_{k-1}^* = a_k^{inc} H_k H_{k-1}^* \qquad \text{(Eq.10)}$$

For the receiver an additional phase term φ_k is introduced, which shall be used to correct the systematic phase offset caused by the channel. Therefore, the final decision variable at the receiver is

$$v_k^{'} = v_k \cdot e^{j\varphi_k} = a_k^{inc} \cdot e^{j\varphi_k} \cdot H_k \cdot H_{k-1}^* \qquad \text{(Eq.11)}$$

As can be seen from the Equation 11, the useful information a_k^{inc} is weighted with the product $e^{j\varphi_k} \cdot H_k \cdot H_{k-1}^*$ (rotation and effective transfer function of the channel). This product must be real-valued for an error free detection. Considering this, it is best to choose the rotation angle to equal the negative argument of $H_k \cdot H_{k-1}^*$. To derive the desired algorithm for 2-path channels, the nature of $H_k \cdot H_{k-1}^*$ is investigated in the next section.

It is assumed that the 2-path channel exhibits two echoes with energy content unequal zero, i.e. at least two dominant echoes. This assumption yields the impulse response

$$h[q] = c_1\delta_0[q] + c_2\delta_0[q - q_0] \qquad \text{(Eq.12)}$$

with

c_1, c_2	:	complex coefficients representing the path echoes;
q_0	:	delay of the second path echo with respect to the first path echo;
δ_0	:	Dirac pulse; $\delta_0[k] = 1$ for k = 0

$$\delta_0[k] = 0 \quad \text{else}$$

The channel transfer function is obtained by applying a DFT (Eq.9) to Equation 12:

$$H_k = H\left(e^{j\frac{2\pi}{K}k}\right) = c_1 + c_2 \cdot e^{-j\frac{2\pi}{K}kq_0} \qquad \text{(Eq.13)}$$

With Equation 13 the effective transfer function for differential demodulation along the frequency axis is:

$$H_k \cdot H_{k-1}^* = \left(c_1 + c_2 e^{-j\frac{2\pi}{K}kq_0}\right) \cdot \left(c_1^* + c_2^* e^{+j\frac{2\pi}{K}(k-1)q_0}\right)$$
$$= c_a + c_b \cos\left(\frac{\pi}{K} q_0(2k - 1)\right) \qquad \text{(Eq.14)}$$

Assuming a noise free 2-path channel, it can be observed from Equation 14 that the symbols on the receiver side are located on a straight line in case the symbol 1+j0 has been send (see above assumption). This straight line can be characterized by a point

$$c_a = |c_1|^2 + |c_2|^2 \cdot e^{-j\frac{2\pi}{K}q_0} \qquad \text{(Eq.15)}$$

and the vector

$$c_b = 2c_1c_2^* \cdot e^{-j\frac{\pi}{K}q_0} \qquad \text{(Eq.16)}$$

which determines its direction.

With the above assumptions, the following geometric derivation can be performed. A more suitable notation for the geometric derivation of the second embodiment of an EPOC algorithm is obtained if the real part of the complex plane is designated as x = Re{z}, the imaginary part as y = Im{z}, respectively, i.e. z = x+jy. With this new notation, the

straight line, on which the received symbols will lie in case of a noise-free two-path channel, is

$$f(x) = a + b \cdot x \tag{Eq.17}$$

with

$$a = \mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\} \tag{Eq.18}$$

and

$$b = -\frac{\mathrm{Im}\{c_a\} - \frac{\mathrm{Re}\{c_a\}}{\mathrm{Re}\{c_b\}} \cdot \mathrm{Im}\{c_b\}}{\mathrm{Re}\{c_a\} - \frac{\mathrm{Im}\{c_a\}}{\mathrm{Im}\{c_b\}} \cdot \mathrm{Re}\{c_b\}} \tag{Eq.19}$$

Additional noise will spread the symbols around the straight line given by Equations 17 to 19. In this case Equation 19 is the regression curve for the cluster of symbols.

For the geometric derivation of the second embodiment of an EPOC algorithm, the angle φ_k from Equation 11 is chosen to be a function of the square distance of the considered symbol from the origin:

$$\varphi_k = f_K\left(|z|^2\right) \tag{Eq.20}$$

Equation 20 shows that the complete signal space is distorted (torsion), however, with the distances from the origin being preserved.

For the derivation of the algorithm of the second embodiment, $f_K(\cdot)$ has to be determined such that all decision variables v_k' (assuming no noise) will come to lie on the real axis:

$$\mathrm{Im}\left\{(x + jf(x)) \cdot e^{jf_K(|z|^2)}\right\} = 0 \qquad \text{(Eq.21)}$$

Further transformations of Equation 21 lead to a quadratic equation which has to be solved to obtain the solution for φ_k.

In case of a two-path channel, the echo phase offset correction for a given decision variable v_k is

$$v_k' = v_k \cdot e^{j\varphi_k} \qquad \text{(Eq.22)}$$

with

$$\varphi_k = \begin{cases} -a\tan\left(\dfrac{a + b\sqrt{|v_k|^2(1+b^2) - a^2}}{-ab + \sqrt{|v_k|^2(1+b^2) - a^2}}\right) & for \quad |v_k|^2 \geq \dfrac{a^2}{1+b^2} \\ a\tan\left(\dfrac{1}{b}\right) & for \quad |v_k|^2 < \dfrac{a^2}{1+b^2} \end{cases} \qquad \text{(Eq.23)}$$

From the two possible solutions of the quadratic equation mentioned above, Equation 23 is the one solution that cannot cause an additional phase shift of 180 degrees.

The two plots in Figure 15 show the projection of the EPOC algorithm of the second embodiment for one quadrant of the complex plane. Depicted here is the quadratic grid in the sector $|\arg(z)| \leq \pi/4$ and the straight line $y = f(x) = a + b \cdot x$ with a = -1.0 and b = 0.5 (dotted line). In case of a noise-free channel, all received symbols will lie on this straight line if 1+j0 was send. The circle shown in the plots determines the boarder line for the two cases of Equation 23. In the left part, Figure 15 shows the situation before the projection, in the right part, Figure 15 shows the situation after applying the projection algorithm. By looking on the left part, one can see, that the straight line now lies on the real axis with 2+j0 being the fix point

of the projection. Therefore, it can be concluded that the echo phase offset correction algorithm according to the second embodiment fulfills the design goal.

Before the second embodiment of an EPOC algorithm can be applied, the approximation line through the received symbols has to be determined, i.e. the parameters a and b must be estimated. For this purpose, it is assumed that the received symbols lie in sector $|\arg(z)| \le \pi / 4$, if 1+j0 was sent. If symbols other than 1+j0 have been sent, a modulo operation can be applied to project all symbols into the desired sector. Proceeding like this prevents the necessity of deciding on the symbols in an early stage and enables averaging over all signal points of one MCM symbol (instead of averaging over only ¼ of all signal points).

For the following computation rule for the EPOC algorithm of the second embodiment, x_i is used to denote the real part of the i-th signal point and y_i for its imaginary part, respectively (i = 1, 2,..., K). Altogether, K values are available for the determination. By choosing the method of least squares, the straight line which has to be determined can be obtained by minimizing

$$(a, b) = \arg\min_{(\tilde{a},\tilde{b})} \sum_{i=1}^{K} \left(y_i - \left(\tilde{a} + \tilde{b} \cdot x_i\right)\right)^2 \qquad \text{(Eq.24)}$$

The solution for Equation 24 can be found in the laid open literature. It is

$$b = \frac{\sum_{i=1}^{K} \left(x_i - \overline{x}\right) \cdot y_i}{\sum_{i=1}^{K} \left(x_i - \overline{x}\right)^2}, \quad a = \overline{y} - \overline{x} \cdot b \qquad \text{(Eq.25)}$$

with mean values

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{K} x_i, \qquad \overline{y} = \frac{1}{N}\sum_{i=1}^{K} y_i \qquad \text{(Eq.26)}$$

If necessary, an estimation method with higher robustness can be applied. However, the trade-off will be a much higher computational complexity.

To avoid problems with the range in which the projection is applicable, the determination of the straight line should be separated into two parts. First, the cluster's centers of gravity are moved onto the axes, following, the signal space is distorted. Assuming that a and b are the original parameters of the straight line and α is the rotation angle, $f_K(\cdot)$ has to be applied with the transformed parameters

$$b' = \frac{b \cdot \cos(\alpha) - \sin(\alpha)}{\cos(\alpha) + b \cdot \sin(\alpha)}, \qquad a' = a \cdot \left(\cos(\alpha) - b' \cdot \sin(\alpha)\right) \qquad \text{(Eq.27)}$$

Besides the two EPOC algorithms explained above section, different algorithms can be designed that will, however, most likely exhibit a higher degree of computational complexity.

The new mapping method for Multicarrier Modulation schemes presented herein consists in principal of two important aspects. Differential mapping within one MCM symbol along the frequency axis direction and correction of the channel echo related phase offset on the subcarriers at the receiver side. The advantage of this new mapping scheme is its robustness with regard to rapidly changing multipath channels which may occur at high frequencies and/or high speeds of mobile receivers.

ABSTRACT

A method of performing an echo phase offset correction in a multi-carrier demodulation system involves the step of differential phase decoding phase shifts based on a phase difference between simultaneous carriers having different frequencies. An echo phase offset is determined for each decoded phase shift by eliminating phase shift uncertainties related to the transmitted information from the decoded phase shift. The echo phase offsets are averaged in order to generate an averaged offset. Finally, each decoded phase shift is corrected based on the averaged offset.

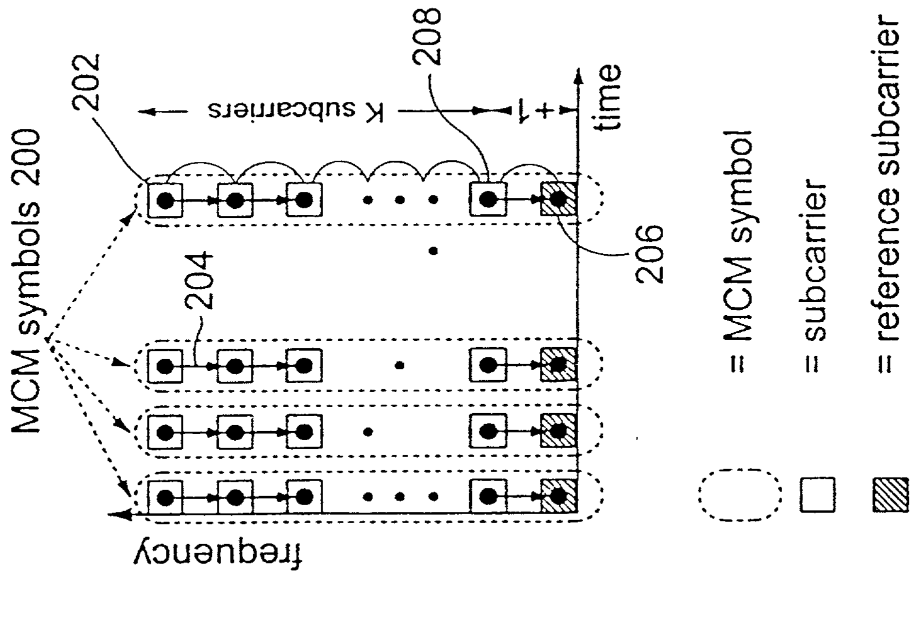

MCM symbols 200
202
204
206
208
K subcarriers
+1
time
frequency
= MCM symbol
= subcarrier
= reference subcarrier

FIG.1

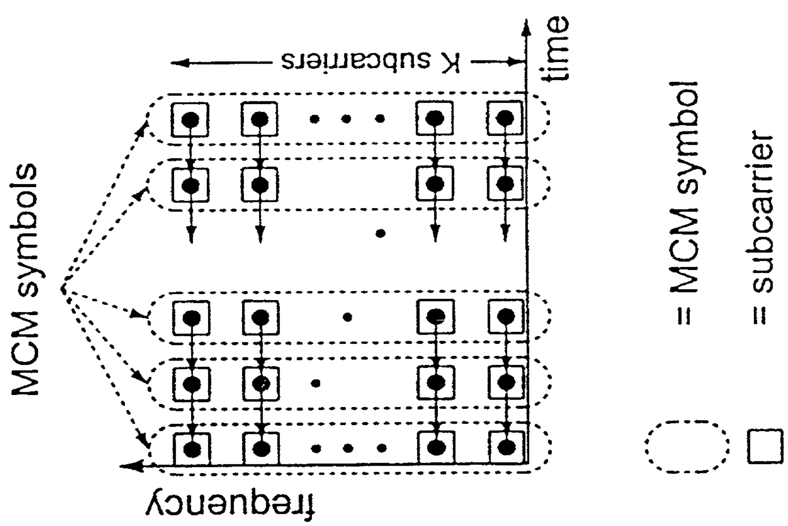

MCM symbols
K subcarriers
time
frequency
= MCM symbol
= subcarrier

FIG.8

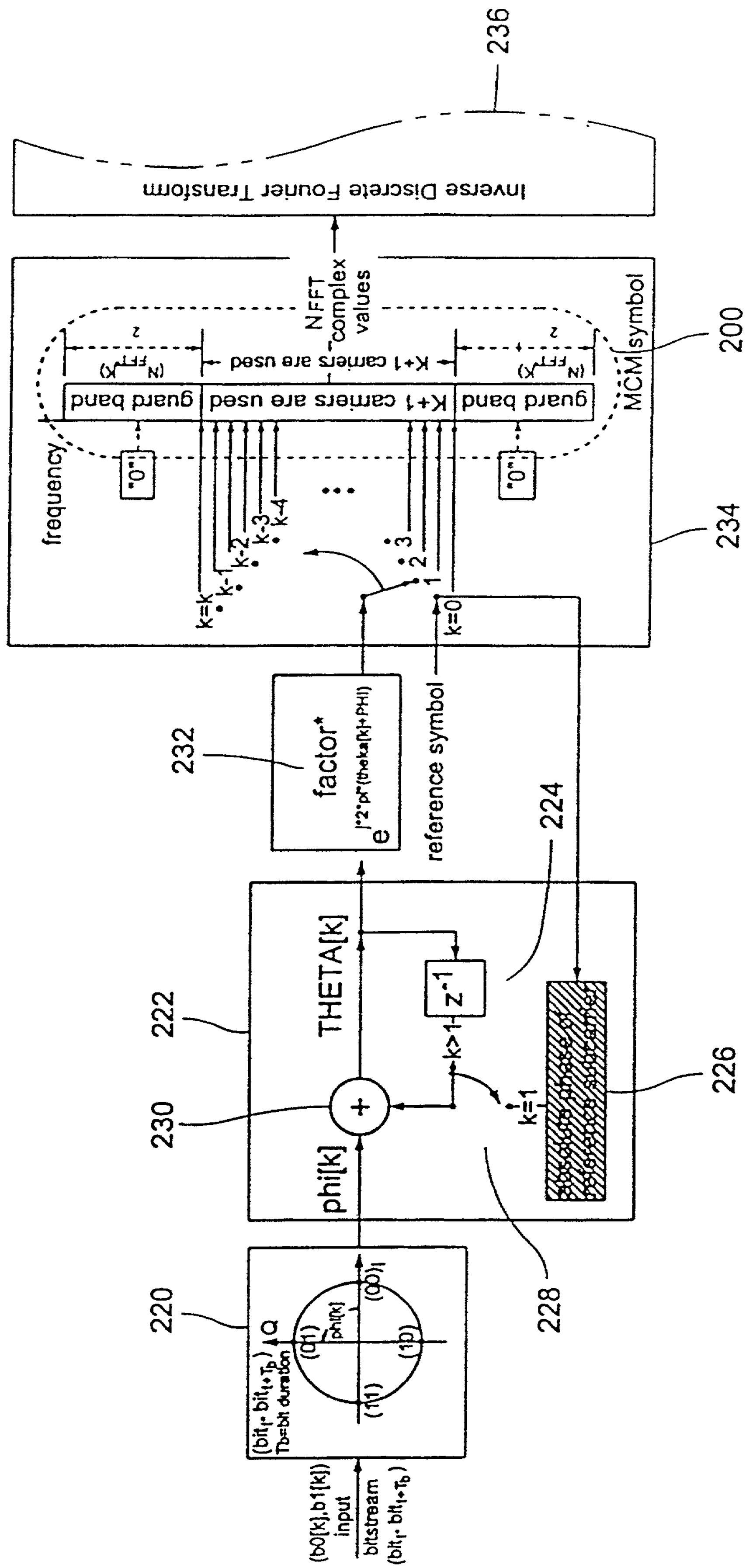

Inverse Discrete Fourier Transform
236
NFFT complex values
guard band
K+1 carriers are used
guard band
MCM symbol
200
234
frequency
"0"
"0"
k=0
reference symbol
factor*
232
THETA[k]
z^{-1}
224
222
phi[k]
230
k>1
k=1
226
228
220
input bitstream
(b0[k],b1[k])

FIG.2

09/673266
PCT/EP98/02167

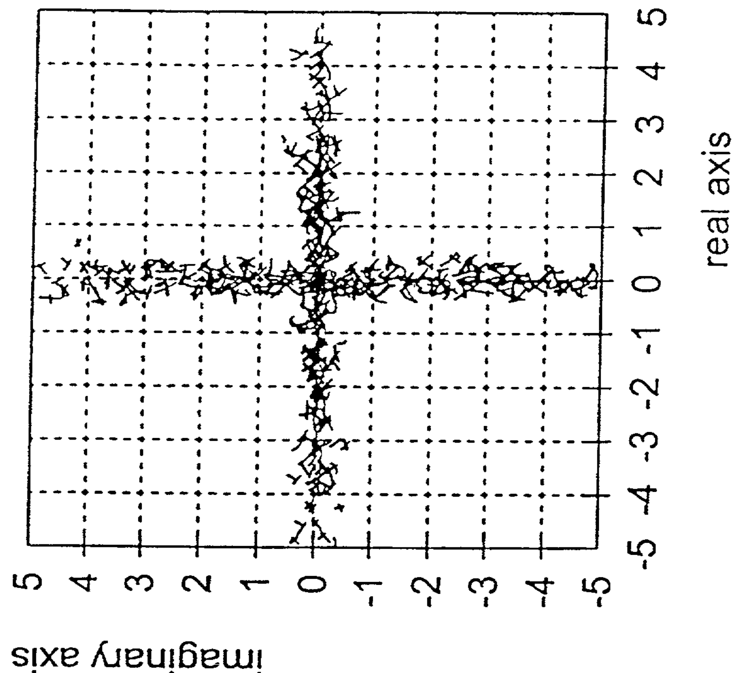


FIG.3B

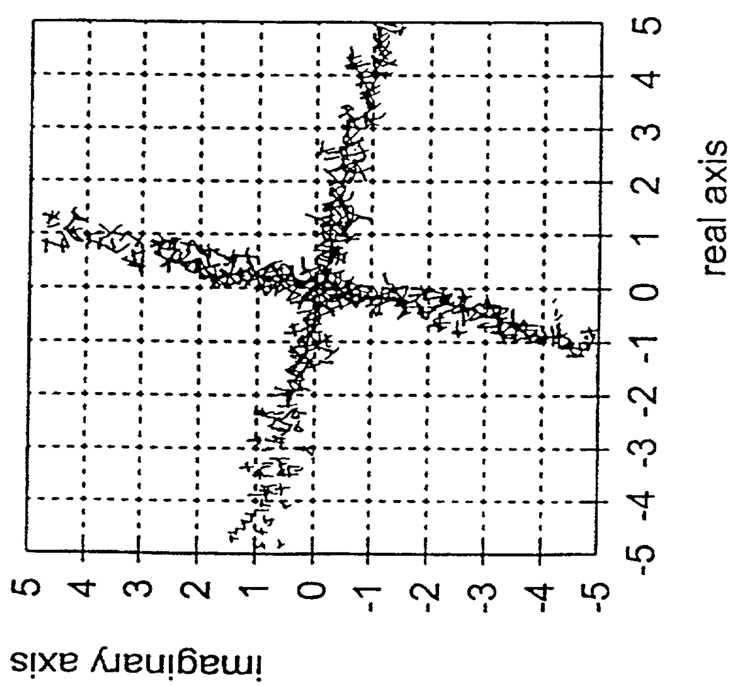


FIG.3A

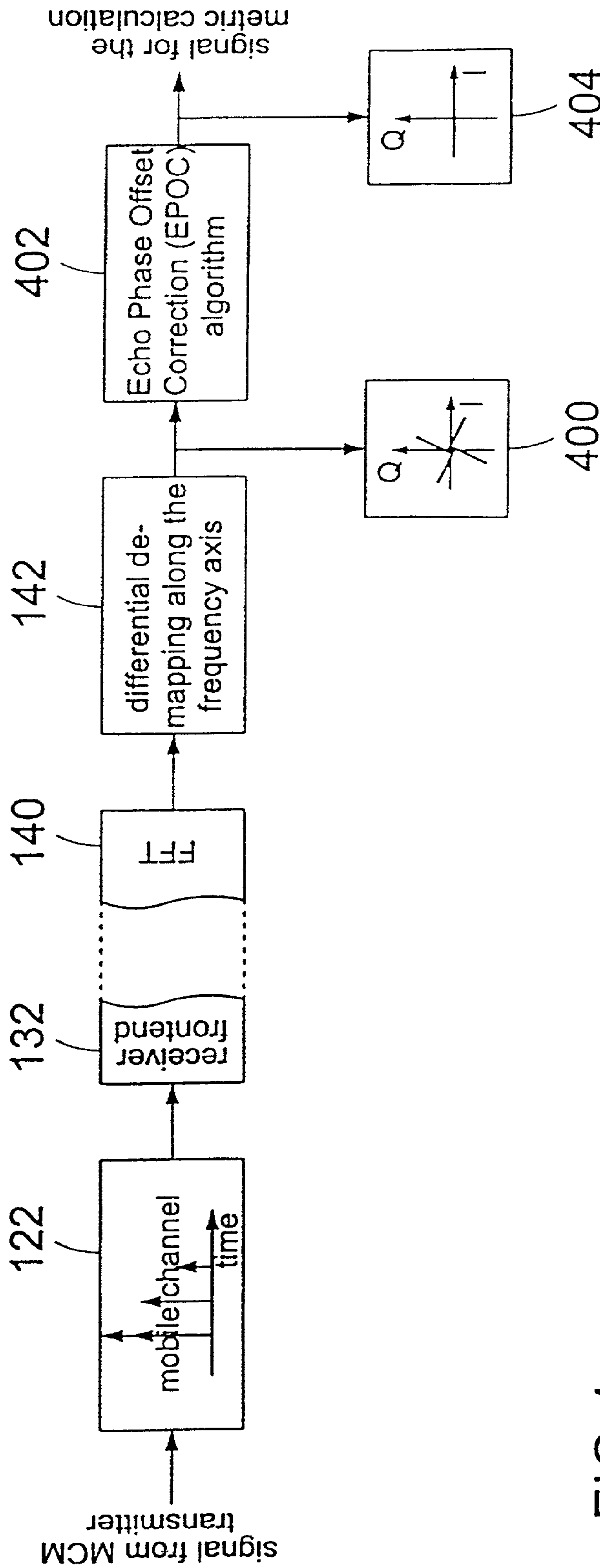
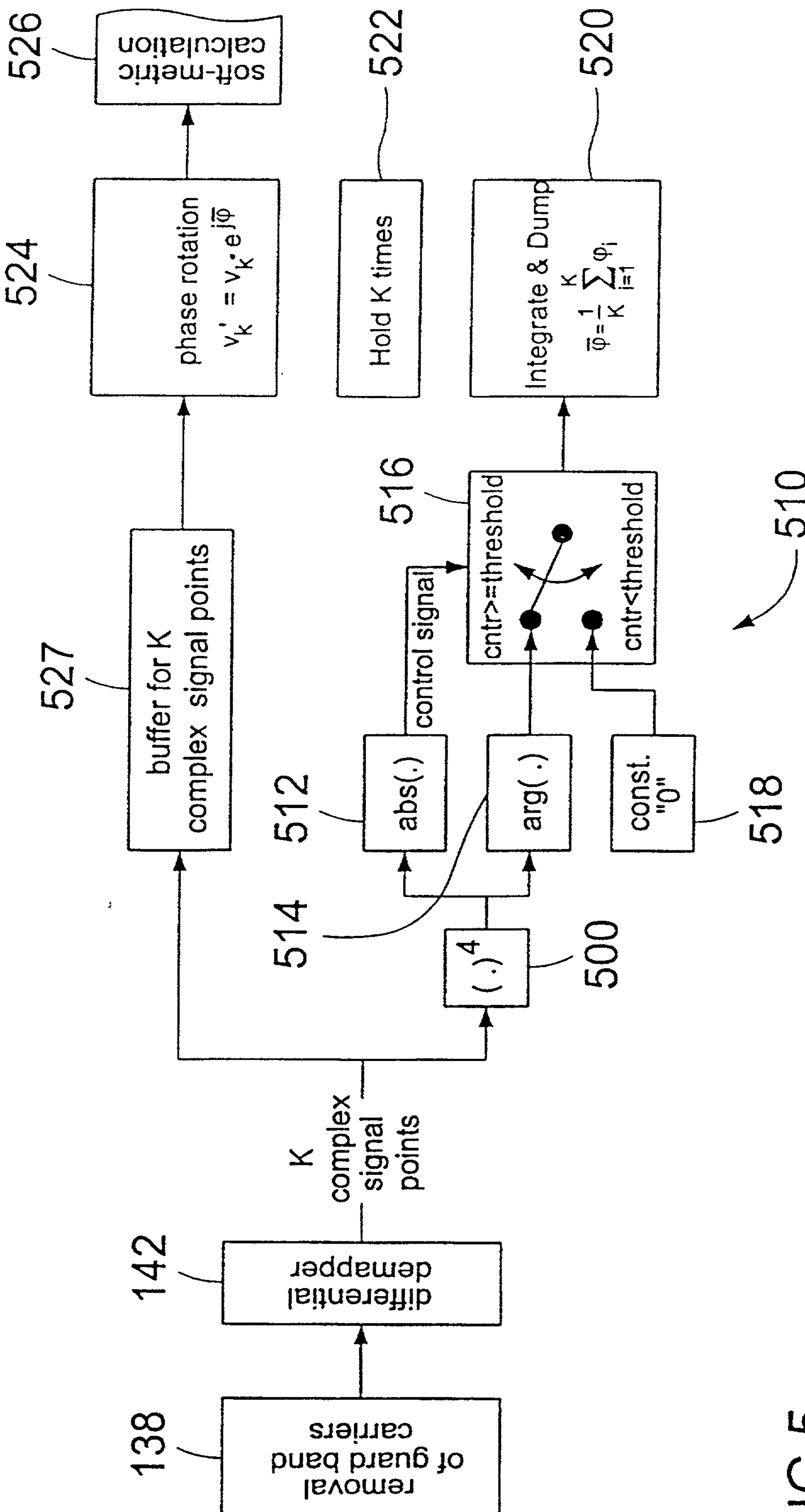

signal from MCM transmitter
122
mobile channel
time
132
receiver frontend
140
FFT
142
differential de-mapping along the frequency axis
402
Echo Phase Offset Correction (EPOC) algorithm
signal for the metric calculation
400
Q
I
404
Q
I

FIG.4



138
removal
of guard band
carriers
142
differential
demapper
K
complex
signal
points
500
(.)^4
514
512
abs(.)
arg(.)
const.
"0"
518
control signal
516
cntr>=threshold
cntr<threshold
510
527
buffer for K
complex signal points
524
phase rotation
$v_K' = v_K \cdot e^{j\bar{\varphi}}$
526
soft-metric
calculation
522
Hold K times
520
Integrate & Dump
$\bar{\varphi} = \frac{1}{K}\sum_{i=1}^{K}\varphi_i$

FIG.5

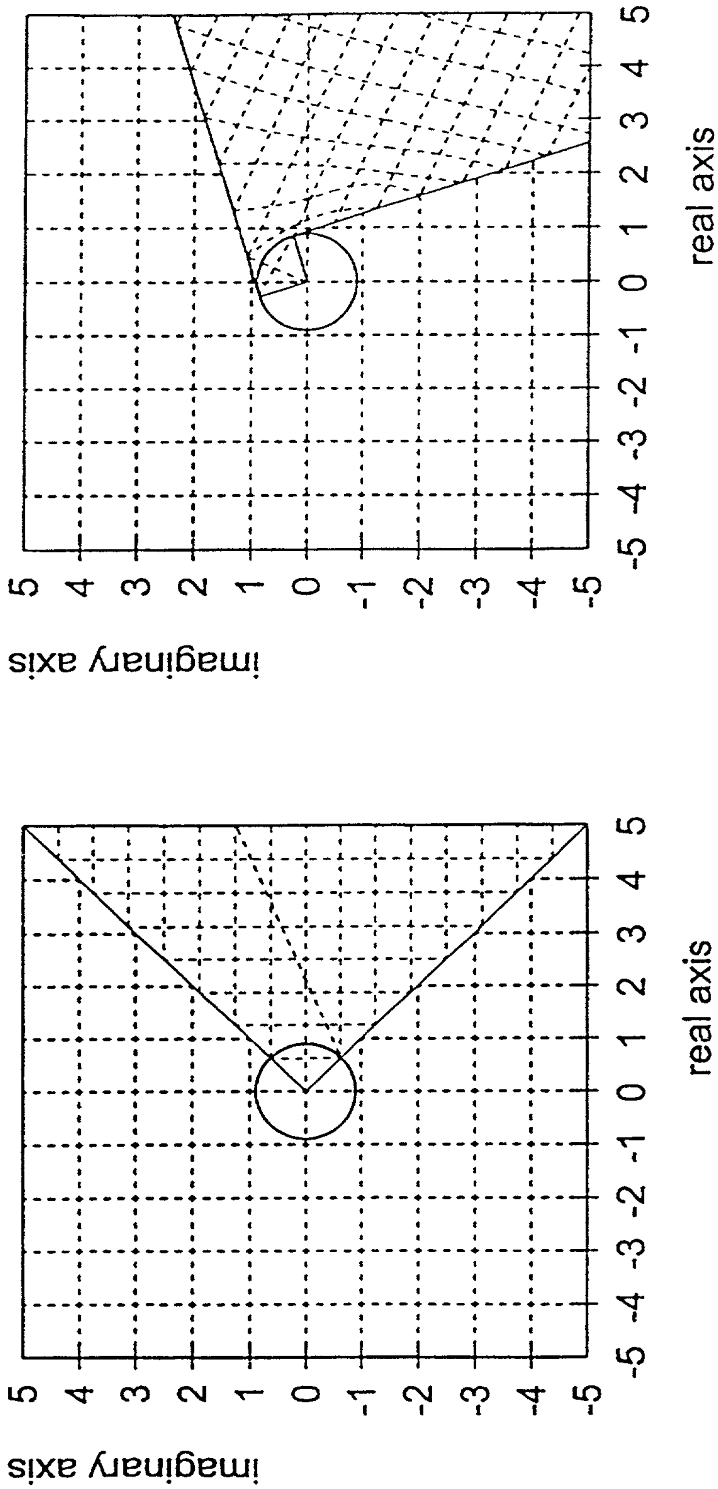


FIG.6

09/673266

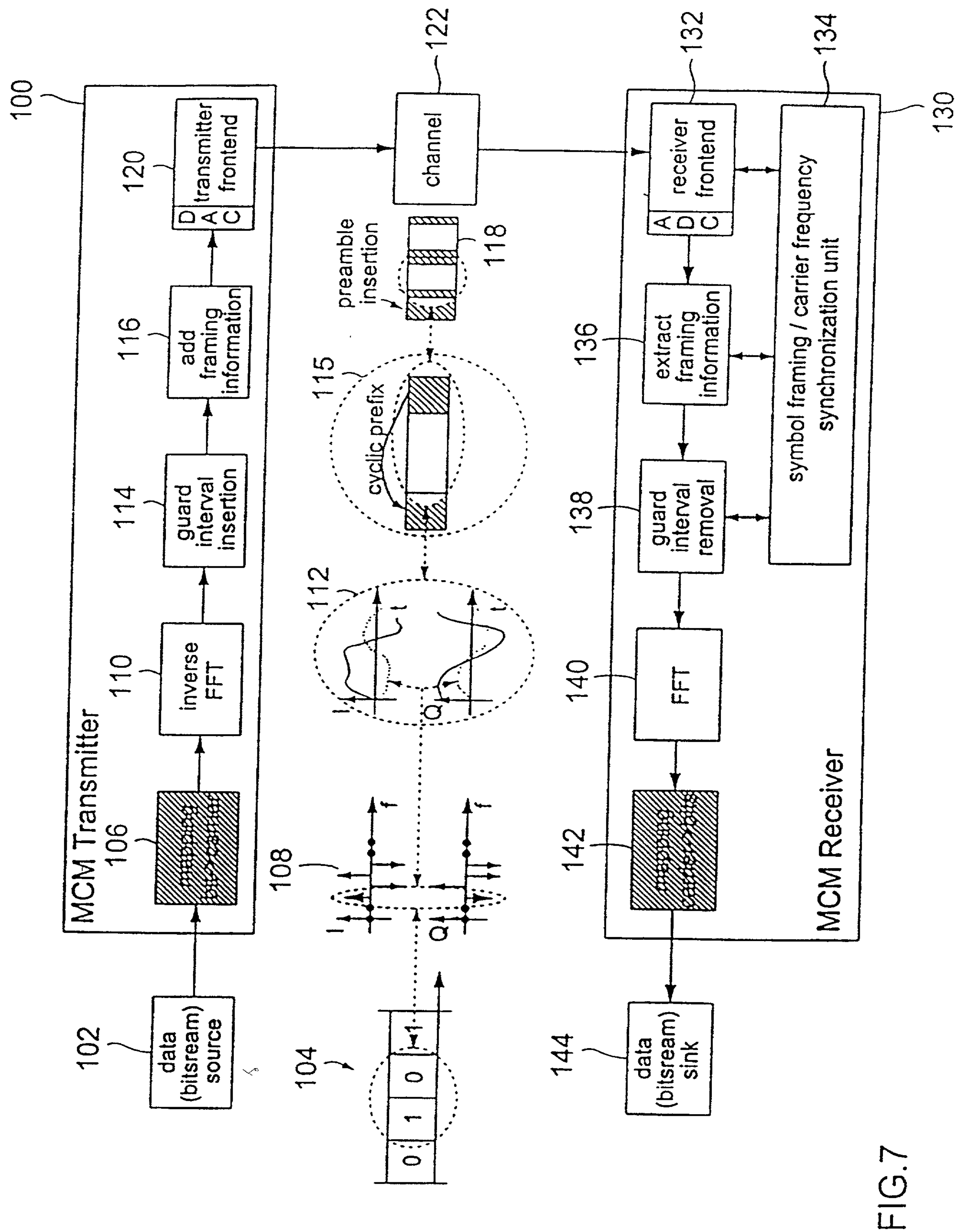


FIG.7

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DECLARATION

ADDITIONAL INVENTOR(S)
Supplemental Sheet
Page 1 of 2

Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

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City	Erlangen	State		ZIP	D-91058	Country	Germany

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City	Erlangen	State		ZIP	D-91058	Country	Germany

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Given Name (first and middle [if any])				Family Name or Surname			
Stephan				Buchholz			
Inventor's Signature						Date	
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Post Office Address							
City	Muenchen	State		ZIP	D-81447	Country	Germany

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Given Name (first and middle [if any])	Family Name or Surname
Albert	Heuberger

Inventor's Signature	Albert Heuberger					Date	11/21/00
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Post Office Address							
City	Erlangen	State		ZIP	D-91056	Country	Germany

Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

Given Name (first and middle [if any])	Family Name or Surname
Heinz	Gerhaeuser

Inventor's Signature	Heinz Gerhaeuser					Date	11/21/00
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Post Office Address							
City	Waischenfeld	State		ZIP	D-91344	Country	Germany

Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

Given Name (first and middle [if any])	Family Name or Surname
Robert	Fischer

Inventor's Signature						Date	
Residence: City	Erlangen	State		Country	Germany	Citizenship	German
Post Office Address	Schubertstrasse 13						
Post Office Address							
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DECLARATION FOR UTILITY OR DESIGN PATENT APPLICATION (37 CFR 1.63)

☐ Declaration Submitted with Initial Filing OR ☑ Declaration Submitted after Initial Filing (surcharge (37 CFR 1.16 (e)) required)

Attorney Docket Number	41002
First Named Inventor	Ernst Eberlein
COMPLETE IF KNOWN	
Application Number	/
Filing Date	
Group Art Unit	
Examiner Name	

As a below named inventor, I hereby declare that:

My residence, post office address, and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:

Echo Phase Offset Correction in a Multi-Carrier Demodulation System

(Title of the Invention)

the specification of which

☐ is attached hereto

OR

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			☐	☐	☐
			☐	☐	☐

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Application Number(s)	Filing Date (MM/DD/YYYY)	
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09/423591

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U.S. Parent Application or PCT Parent Number	Parent Filing Date (MM/DD/YYYY)	Parent Patent Number *(if applicable)*

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Robert H. Berdo	19,415	Joseph J Buczynski	35,084
Alfred N. Goodman	26,458	Wayne C Jaeschke, Jr.	38,503
Mark S. Bicks	28,770	Tara Laster Hoffman	P-46,510
John E. Holmes	29,392	Jeffrey J. Howell	46,402
Garrett V. Davis	32,023	Marcus R. Mickney	44,941
Lance G. Johnson	32,531	Christian C. Michel	46,300

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Direct all correspondence to: ☐ Customer Number or Bar Code Label [ ] *OR* ☑ Correspondence address below

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Address	1300 19th Street, N.W., Suite 600				
City	Washington	State	D.C.	ZIP	20036
Country	USA	Telephone	(202)659-9076	Fax	(202)659-9344

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under 18 U.S.C. 1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Name of Sole or First Inventor: ☐ A petition has been filed for this unsigned inventor

Given Name (first and middle [if any])	Family Name or Surname
Ernst	Eberlein

Inventor's Signature	[signature]					Date	11/21/00
Residence: City	Grossenseebach	State		Country	Germany	Citizenship	German
Post Office Address	Waldstrasse 28 b						
Post Office Address							
City	Grossenseebach	State		ZIP	D-91091	Country	Germany

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(Title of the Invention)

the specification of which
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OR
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			☐	☐	☐

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Address	1300 19th Street, N.W., Suite 600				
City	Washington	State	D.C.	ZIP	20036
Country	USA	Telephone	(202)659-9076	Fax	(202)659-9344

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Given Name (first and middle [if any])	Family Name or Surname
Ernst	Eberlein

Inventor's Signature						Date	
Residence: City	Grossenseebach	State		Country	Germany	Citizenship	German
Post Office Address	Waldstrasse 28 b						
Post Office Address							
City	Grossenseebach	State		ZIP	D-91091	Country	Germany

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Page 1 of 2

Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

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Stefan	Lipp

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Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

Given Name (first and middle [if any])	Family Name or Surname
Stephan	Buchholz

Inventor's Signature	Stephan Buchholz					Date	11/20/00
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Post Office Address							
City	Muenchen	State		ZIP	D-81447	Country	Germany

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Given Name (first and middle [if any])	Family Name or Surname
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Heinz	Gerhaeuser

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Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

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Robert	Fischer

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Post Office Address							
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Name of Sole or First Inventor: ☐ A petition has been filed for this unsigned inventor

Given Name (first and middle [if any])	Family Name or Surname
Ernst	Eberlein

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☐ Additional inventors are being named on the ____supplemental Additional Inventor(s) sheet(s) PTO/SB/02A attached hereto

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DECLARATION

ADDITIONAL INVENTOR(S)
Supplemental Sheet

Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

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Sabah	Badri

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Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

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DECLARATION

ADDITIONAL INVENTOR(S)
Supplemental Sheet
Page 2 of 2

Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

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Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

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Name of Additional Joint Inventor, if any: ☐ A petition has been filed for this unsigned inventor

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